

Master Thesis in Geosciences

Age and geochemistry of some intrusives from the East Greenland Caledonides

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UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Abstract

The East Greenland Caledonides stretches from c. 70° to 80° N, and was formed during the subduction of the Baltican plate under the Laurentian plate in Late Ordovician- Early Silurian. Liverpool Land is thought to be a part of the Uppermost Allochthon, described from the Norwegian Caledonides, in the East Greenland Caledonides.

Two of the most extensive intrusives on the Liverpool Land is the Hurry Inlet Granite and the Hodal-Storefjord Monzodiorite, which have been dated to c. 440 Ma and c. 424 Ma respectively. They are thought to be part of an extensive Caledonian intrusive belt, stretching from Scotland through East Greenland to Norway. Geochemical analysis of these granitoids show a clear arc signature and comparison with granites from Renland, Scotland and northern Norway suggest they are linked to the same event.

Emplacement of these granites was probably caused by dehydration of the subducting slab, causing partial melting of the mantel wedge leading to underplating in the lower crust. Heat from this underplating may thus have caused further partial melting of the crust. Due to the buoyancy of melts, mingling of the more mafic magma, from the mantel wedge, with the more felsic magma, from the crust, may have caused the occurrence of mafic enclaves of the same age.

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1 Introduction

This thesis is a contribution to an ongoing research project at the Department of Geoscience at the University of Oslo, lead by Professor Arild Andresen, focusing on the evolution of the East Greenland Caledonides (Figure 1). An important aspect of this project is to test if the Uppermost Allochthon, in the Norwegian Caledonides, is of Laurentian affinity or not. The focus of this thesis is the age of magmatism, and the plate tectonic setting of the Liverpool Land intrusives (East Greenland) (Figure 2), and their possible connections to granitoids in the Scottish and Norwegian Caledonides, particularly the Helgeland Nappe Complex.

Granitic rocks are common in the East Greenland Caledonides, which stretches from c.70°N to c.80°N (Figure 2). Most of the intrusives are two-mica leucogranites interpreted to have formed by anatexis of the Late Mezoproterozoic Krummedal Sequence (Strachan et al. 2001, Kalsbeek et al. 2001a., Jones and Escher 2002, Andresen et al. 2007, Kalsbeek et al. 2008). Both Caledonian (c.435-425 Ma) (Strachan et al. 2001, Higgins et al. 2004, Andresen et al. 2007) and older (c.950-900 Ma) (Kalsbeek et al. 2000, Watt et al. 2000, Leslie and Nutman 2003) granites are found. The Caledonian ages are taken from different structural levels, and together with field observations suggest that melt emplacement occurred contemporaneous with upper crustal extension and lower crustal contraction (Strachan et al. 2001, Andresen et al. 2007).

Whereas two-mica granites dominate in the Keiser Franz Joseph Fjord and Kong Oscar Fjord area (Figure 2) the Liverpool Land area further east is characterized by large volumes of different types of inferred intrusives. As part of a mapping campaign by the Grønlands Geologiske Undersøgelse it was recognised that the granitoids ranged from pre- to post-kinematic, and with composition varying from leucocratic mica granite to mesocratic monzodiorite (Coe and Cheeney 1972, Coe 1975).

The largest granitic intrusive in Liverpool Land is the Hurry Inlet granite, which was first mapped and described by Kranck (1935), and later by Coe (1975) and Augland (2007). Coe and Cheeney (1972) also described several other intrusive bodies, among them the Hodal-Storefjord monzodiorite. The occurrence of amphibole and orthopyroxene in these granitic bodies indicates that these plutons have a different genesis than the typical two-mica granites further west, described by Kalsbeek et al. (2001b.). The difference between the Liverpool

Land granitoids and the two-mica granites is further supported by the geochemical data presented by Coe (1975) and Kalsbeek et al. (2001a.).

The purpose of this master thesis is to generate new geochemical data, based on samples collected from a monzodiorite body (Hodal-Storefjord Monzodiorite) and a neighbouring granitic body (Hurry Inlet Granite) at Liverpool Land (Figure 1) (c. 70°59 N), try to put these data into a plate tectonic setting, and to investigate if this magmatism is connected to an older phase of Caledonian magmatism than the two-mica granites. Following this a comparison with the age of magmatism in Scotland and/or Helgeland Nappe Complex will be carried out.

2 Geological setting

The Caledonian Orogen formed in the early Paleozoic as a result of the collision between Laurentia and Baltica following the closure of the Iapetus ocean (Roberts and Gee 1985). During the final stages of collision, the Baltican plate was subducted underneath the Laurentian plate, a process which resulted in the formation of an orogenic belt of the similar size as the modern day Himalayas (Andersen 1998). Pieces of the Caledonian Orogenic belt are today found in Western Scandinavia, in Svalbard, in East Greenland, the British Isles and in Eastern North America (Figure 1).

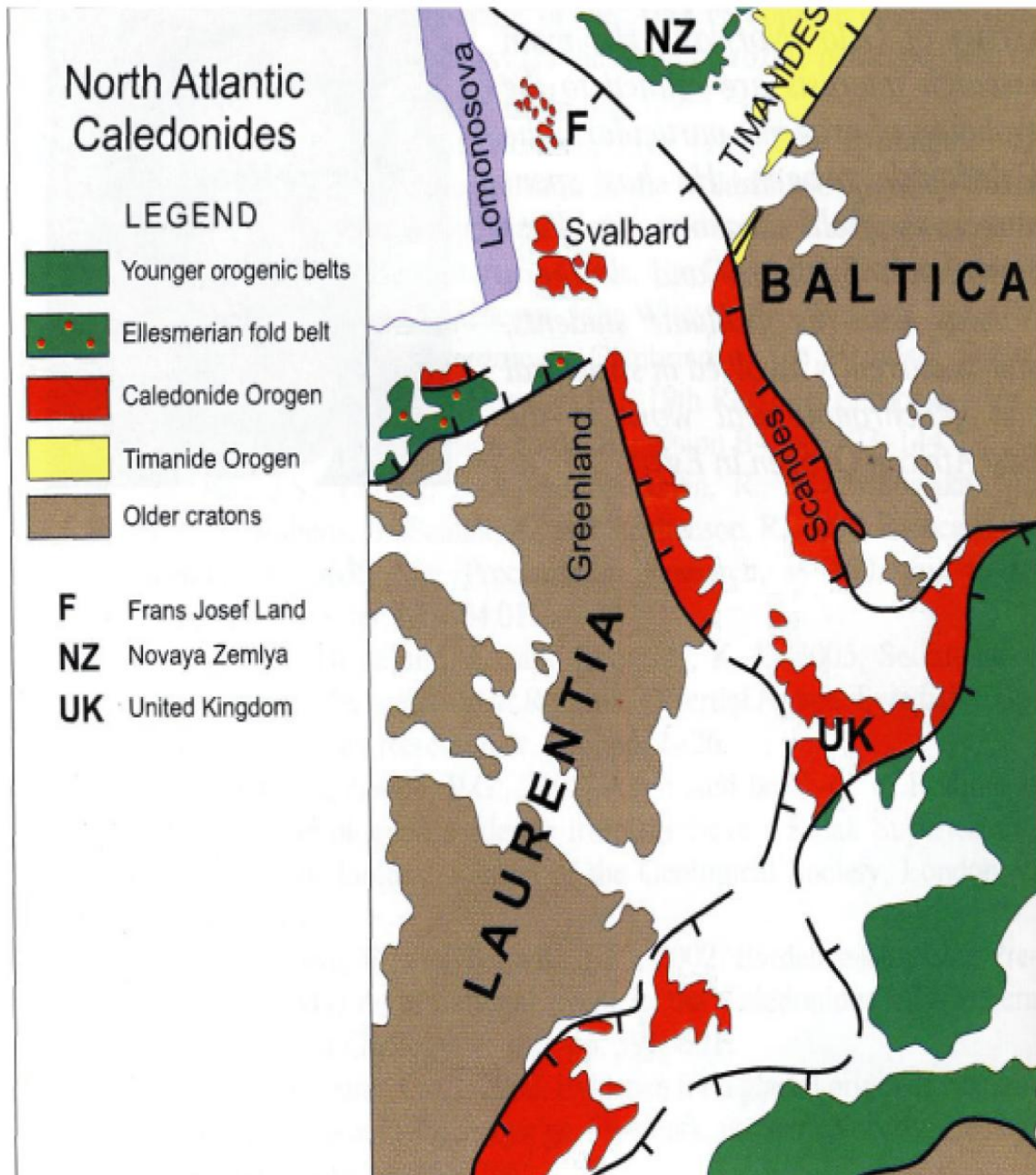


Figure 1: The spread of the Caledonian orogen is shown on the map. Red color marks the Caledonian orogen, brown color marks older cratons, yellow the Timanide orogen and green younger orogenic belts. From Gee et al. (2008)

The initiation of this closure probably started with the closure of the Tornquist Sea, between Avalonia and Baltica (Torsvik et al. 1996), that by the late Ordovician to early Silurian had closed enough to form Balonia (Torsvik et al. 1996). This was most likely not a full scale continent –continent collision, but probably initiated the closure of the Iapetus ocean. The collision between Baltica and Laurentia was probably oblique, and caused a subduction of

Balonia (see above) under a stationary Laurentia in an early Scandian event ~ 425 Ma (Torsvik et al. 1996), with extreme crustal thickening. This sinistral transpressive deformational event and associated Scandian thrusting continued until Devonian times in the northern areas of Norway.

Collision between Baltica and Laurentia resulted in emplacement of far-travelled thrust sheets towards the Baltican and Laurentian foreland. The Scandinavian Caledonides are traditionally divided into 5 major tectonostratigraphic units (Roberts and Gee 1985). These are from the base upwards, (1) the autochthonous-parautochthon Fennoscandian basement and its sedimentary cover, (2) the Lower Allochthon composed of low grade sediments of Neoproterozoic to early Paleozoic age, (3) the Middle Allochthon dominated by large crystalline nappe complexes, (4) the Upper Allochthon with mainly ophiolites and island-arc complexes (Andersen 1998), and (5) the Uppermost Allochthon. Whereas the Lower and Middle Allochthons are interpreted to be of Baltic affinity are most rocks of the Upper Allochthon and the Uppermost Allochthon by most authors interpreted to be exotic with respect to Baltica (Roberts et al. 2002, Steltenpohl et al. 2003). In recent years several authors (e.g. Roberts 2003, Barnes et al. 2007) have argued that rocks involved in the uppermost Allochthon area derived from Laurentias eastern margin (Scotland/ East Greenland).

The East Greenland Caledonides were, by Haller (1971) divided into two principally different lithotectonic units, the Precambrian basement complex and a great pile of geosynclinal Neoproterozoic sediments ~ 16 km thick (Haller 1971), divided into the Eleanor Bay Group and the Tillie Group. Recent mapping by the Geological Survey of Denmark and Greenland (1997-1998), resulted in a discovery of several tectonic windows, which gave new insight in the stratigraphic division (Higgins and Leslie 2000 and references therein). Today most authors accept a sub-division into an autochthonous to parautochthonous basement complex of Paleo- to Mezoproterozoic age with a Neoproterozoic to Lower Paleozoic cover, tectonically overlain by a regionally extensive thrust sheet (Higgins et al. 2001). The Allochthonous thrust sheet comprises three main lithotectonic units (Higgins and Leslie 2000) which are: (1) Paleoproterozoic or older crystalline rocks overlain by (2) a variably metamorphosed Mezoproterozoic metasedimentary successions, the Krummedal Sequence, and a (3) low grade metasedimentary sequence of Neoproterozoic to Early Paleozoic age, subdivided into the Eleonore Bay Supergroup (EBS), the Tillite Group and the Kong Oscar Fjord Group (Higgins et al. 2004).

Higgins and Leslie (2000) have argued that the internal structure of the allochthon/thrust sheet in the Fjord Region (72-74 °N) is composed of two major thrust sheets, the Niggli Spids and the Hagar Bjerg Thrust Sheets, which both contain Paleoproterozoic crystalline basement, the Mezoproterozoic Krummedal Sequence and an upper Franz Joseph Allochthon consisting of the EBS, locally overlain by tillites and Lower Paleozoic sediments (Higgins and Leslie 2000, Higgins et al. 2004). The entire package is thrust over a parautochthonous foreland. The upper thrust sheet, Hagar Bjerg Thrust Sheet is, intruded by Caledonian and Grenvillian granitoids (Higgins and Leslie 2000, Higgins et al. 2004). The Franz Joseph Allochthon is only intruded by the Caledonian granitoids. The contact between Hagar Bjerg and Franz Joseph Allochthons is considered to be a thrust modified by extensional faulting (Higgins et al. 2004).

An alternative interpretation has been proposed by Andresen et al. (2007). These authors interpreted the repetition of units in the allochthon as a result of recumbent folding instead of thrusting, and thus considered the Niggli Spids and Hagar Bjerg to belong to the same thrust sheet, named the Niggli-Hagar Thrust Sheet. In the descriptions and discussions which follows, the terminology of Andresen et al. (2007) will be used.

Both Higgins et al. (2004) and Andresen et al. (2007) agree that the whole nappe stack is dissected by two late orogenic extensional fault or detachments with top-to-the-east displacement, called the Nunatak Fault (Andresen et al. 1998) or the Boyd Bastionen Fault (Higgins et al. 2004), and the Fjord Region Detachment (Andresen et al. 1998) respectively. The Fjord Region Detachment was active from late Silurian (Hartz et al. 2001) to at least Early Carboniferous (White and Hodges 2002).

The foreland and parautochthonous basement is largely covered by inland ice, but crops out in northern East Greenland, Kronprins Christian Land, and in several tectonic windows further south along the east coast (Higgins et al. 2001, Higgins et al. 2004) (Figure 2). Figure 3 gives a schematic overview of the Caledonian orogen the Fjord Region area.

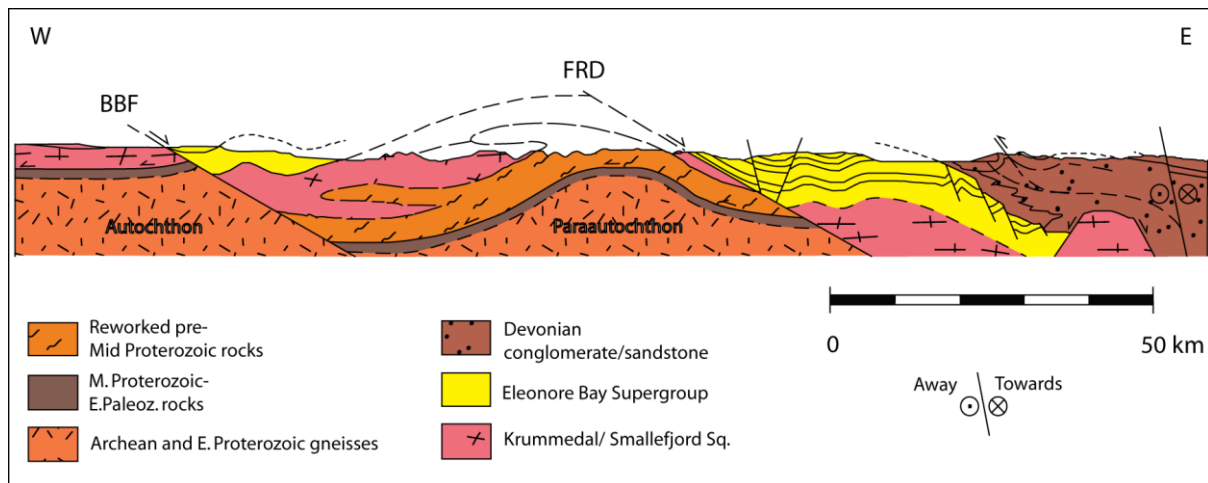


Figure 3: A schematic profile across the Caledonian orogen from the Fjord region area, marked by a black line in Figure 1. After Andresen et al. (2007).

2.1 Basement-cover relationships in the foreland and the tectonic windows.

Kronprins Christian Land (79°30')

In Kronprins Christian Land there is a complete section through the Neoproterozoic- Early Paleozoic stratigraphy of the Caledonian foreland (Higgins et al. 2001). Parts of this foreland succession are also exposed in several tectonic windows further south. The successions seen in the windows show evidence of Caledonian deformation, and is by Higgins and Leslie (2000) interpreted to be parautochthonous rather than autochthonous. West of Danmark Fjord, Proterozoic foreland successions are well exposed and there comprise thick Paleo- to Mezoproterozoic sequences overlain by Neoproterozoic- Lower Paleozoic shelf sediments (Higgins et al. 2001). The older sequence is the Independence Fjord Group and the Zig Zag Dal Basalt Formation (Collinson 1980, Higgins et al. 2001). Above here we have the Neoproterozoic shelf sediments of the Hagen Fjord Group and then a well-defined but in detail obscured contact with the Cambrian Kap Holbæk Formation (Smith et al. 2004), defined as a hiatus. Another hiatus occurs between the Kap Holbæk Formation and the overlying Ordovician-Silurian platform carbonates (Higgins et al. 2001). The autochthonous foreland is bounded to the west by a thrust sheet, called the Vandredalen Thrust sheet, which

displaces Neoproterozoic clastic sediments across the parautochthonous foreland, and thus gives a maximum age of thrusting (Higgins et al. 2001).

Lambert Land (79°20'N)

The Lambert Land window is dominated by crystalline basement gneiss complexes and sandstones of the Independent Fjord Group (Higgins et al. 2001), these have been interleaved in major Caledonian Thrust Sheets (Higgins et al. 2001 and references therein). In the westernmost Lambert Land the erosional surface underneath the Wandel Valley Formation, has breached the Hagen Fjord Group to lie within the Independence Fjord Group (Smith et al. 1999). Conodont color alteration indices (CAI) values from the Ordovician carbonates in the western part of Lambert Land, shows the similar values as the conodonts of the Vandredalen Thrust Sheet in Kronprins Christian Land, which indicate a burial depths of 10-12,5 km (Higgins et al. 2001). This unconformity suggest that the overstep at the base of the Wandel Valley Formation, progressed both south- and east-wards (Bryant and Smith 1990, Smith et al. 1999).

Nørreland Window (78°40')

Here we find Mezoproterozoic quartzite's, that are comparable with the Independence Fjord Group, cut by a network of dolorite dikes that crop out in an anticlinal window (Higgins et al. 2001, Augland 2007). This complex is overlain by deformed Ordovician metacarbonates, which yields CAI values that indicates an overburden of 10-12,5 km (Rasmussen and Smith 2001). A thrust sheet of crystalline basement containing amphibolites and orthogneisses, which locally contains eclogites of Devonian age (Gilotti 1993, Brueckner et al. 1998, Gilotti et al. 2004) overlies the carbonates. Thus this thrust sheet must have gone through thinning before it was thrust westward no earlier than ca.390 Ma (Gilotti et al. 2004).

Dronning Louise Land (75°50'-77°25')

The foreland is here separated from a allochthonous Proterozoic gneiss complex by a N-S trending imbricate zone (Higgins et al. 2001), which represents the western limit of intense Caledonian deformation. The underlying foreland are less deformed and contains a succession of metasediments, of the Trekant `series`, that is cut by dolorite dikes correlated with the

Independence Fjord Group of Kronprins Christian Land (Haller 1971, Higgins et al. 2001). This is again overlain by the younger and thin sequence of the Zebra 'series', which contains Skolithos and is correlated with the Kap Holbæk Formation of Kronprins Christian Land (Friderichsen et al. 1990, Clemmensen and Jepsen 1992, Higgins et al. 2001)

Tucker et al. (1993) gives an age for the Caledonian reworking of the allochthonous basement in the eastern Dronning Louise Land provided by a lower concordia intercept of c. 422 Ma for the granitic orthogneiss. This age is comparable with the $^{40}\text{Ar}/^{39}\text{Ar}$ mineral cooling ages from other lithologies in the Caledonides in North-East Greenland (Tucker et al. 1993 and references therein)

Eleonore Sø Window (73°35'-74°25')

The Eleonore Sø window exposes a volcano-sedimentary complex which comprises arkosic psammites and semipelites overlain by a carbonate sequences, a sequence of quartzose psammites and black shale's, and a envisaged rift related lava sequence on top (Higgins and Leslie 2000, Higgins et al. 2001). A body of Quartz porphyry intruding into the sequence is dated to 1900 Ma, and would thus indicate a Paleoproterozoic age (Higgins et al. 2001 and references therein). Unconformably overlying this sequence is the Slottet Formation, a 350 m thick sedimentary sequence consisting of basal conglomerate and several quartzite beds. *Skolithos* observed in the upper sequence are abundant, and correlation can be made to the Zebra 'series' and the Kap Holbæk Formation (Higgins et al. 2001). Above the Slottet Formation there is a up to 50 m sequence of weathered carbonates underlying a major Caledonian thrust, interpreted to be of Cambrian age (Higgins et al. 2001).

Målebjerget Window

Approximately 35 km east of the Eleonore Sø window, the Slottet Formation rests unconformably on basement gneisses. According to Higgins (1970) the Målebjerget succession includes three members, in ascending order: a) Sericite-chlorite schist to augen gneiss, b) white quartzite and last c) marbles and calcareous chlorite schist's. In the Målebjerget window, the Målebjerget Formation, consisting of Cambro-Ordovician carbonates, is overlying the Slottet Formation (Higgins et al. 2001)

Charcot Land Window (71°30′-72°10′)

In Charcot Land, the infracrustal gneisses, unconformably overlies the volcanosedimentary sequence below an arched major thrust (Higgins et al. 2001). This region is considered to be part of the Caledonian foreland, and is cut by quartz diorite and granite intrusions through the supracrustal sequence and the crystalline basement (Higgins et al. 2001). They both yield Palaeoproterozoic isotope ages, and are considered to indicate the time of emplacement, thus it has been suggested a correlation between the Charcot Land supracrustal sequence and the supracrustal rocks in the Eleonore Sjø region (Higgins et al. 2001).

An outcrop of diamictite is also found here, which is interpreted to be tillite and correlated with the tillite in the Fjord Region (Henriksen 1981, Moncrieff 1989, Higgins et al. 2001). It occurs structurally below a major Caledonian thrust, which indicates displacement of at least 40 km (Henriksen 1981).

Gåseland Window (70°10′-70°40′)

The southernmost tectonic window, is the Gåseland Window, which crops out in western Gåseland, adjacent to the inner Scoresby Sund region (Higgins et al. 2001). Here, similar to the Charcot Land and Målebjerget windows, a crystalline basement complex is unconformably overlain by diamictite, interpreted as tillite, preserved in pockets on the gneiss surface at the base of a thin sequence of calcareous sediments (Henriksen and Higgins 1976, Higgins et al. 2001). The tillites here are also correlated by Phillips and Friderichsen (1981) to the Tillite group in the Fjord Region.

2.2 Basement-cover relationship along the Caledonian Orogen

The transition between the Caledonian orogen and the undisturbed foreland is well preserved in Kronprins Christian Land, while the other windows further south, show variable degree of Caledonian deformation (Higgins et al. 2001). There exists a broad similarity in autochthonous foreland and parautochthonous units exposed in the tectonic windows along the East-Greenland Caledonides (Higgins et al. 2001). In all the tectonic windows, carbonates of Early Paleozoic age are found, except in Charcot Land (Higgins et al. 2001). In Kronprins Christians Land, Lambert Land and Nørreland windows conodonts of Ordovician age are found, and in Målebjerg and Eleonore Sø carbonates also indicate a post-Proterozoic age (Higgins et al. 2001). Lower Cambrian quartzites, containing *Skolithos*, underlies these carbonates in Kronprins Christian Land, Dronning Louise Land, Eleonore Sø and in Målebjerg. These, with the occurrence of diamictite in Gåseland, Charcot Land and Målebjerg gives evidence of a coherent N-S striking Iapetus margin (Higgins et al. 2001). All of these observations suggests that the pre-Caledonian sedimentary deposit overlapped the Archean to Early-Proterozoic basement, and according to Soper and Higgins (1993) support the hypothesis that the tectonic windows exposes the rifted margin of the Iapetus.

2.3 Tectonostratigraphy within the Niggli-Hagar Thrust Sheet

2.3.1 Allochthonous crystalline basement with eclogites

The crystalline gneisses making up the lower part of the Niggli-Hagar Thrust Sheet can be divided into an Archean (c. 2,7-2,8 Ga) gneiss unit south of 72°30'N and Paleoproterozoic (c. 1,9-2,0 Ga) gneisses north of this latitude (Thrane 2002). Geochemical data suggests that the transition between the Archean to the Paleoproterozoic basement is a result of subduction of the Paleoproterozoic oceanic crust under the Archean basement (Thrane 2002). The Paleoproterozoic rocks extends north to approximately 81°N, and probably compromise all

the allochthonous crystalline basement rocks north of 72°50'N (Thrane 2002, Augland 2007). Samples of the Paleoproterozoic rocks at c.77°N are dated by Kalsbeek et al. (1993) to be c. 1,74-1,97 Ga.

Eclogites and retrograde eclogites are found over large areas in North-East Greenland between c.76°N and c. 80°N. They occur generally in allochthonous felsic gneisses, and are a part of what is known as the North-East Greenland Eclogite Province (NEGEP) (Gilotti 1993, Brueckner et al. 1998, Gilotti and Ravna 2002, Gilotti et al. 2004). Both high-pressure (HP) (Brueckner et al. 1998, Gilotti et al. 2004) and ultrahigh-pressure (UHP) (Gilotti and Ravna 2002, Gilotti et al. 2004) Caledonian metamorphism has been documented in this area. Timing of the HP-metamorphism has been dated by Gilotti et al. (2004) to c. 401-417 Ma and the UHP-metamorphism by Gilotti and Ravna (2002) to c. 360 Ma. Sartini-Rideout et al. (2006) argues that the NEGEP is divided into a western, central and eastern block by the sinistral Storstrømmen shear zone in the west and the dextral Germania Land deformation zone in the east. Eclogites in the western and central block yields an older age (410-390 Ma) for the HP than for the UHP and HP in the eastern block (UHP c. 360 Ma) (Sartini-Rideout et al. 2006). The initial exhumation of the HP-rock is attributed by Sartini-Rideout et al. (2006) to be caused by transpression and vertical extrusion along the Germania Land deformation zone and the Storstrømmen shear zone, between 370 - 340 Ma. Continuing exhumation in the region is thought to be caused by continuing displacement and brittle faulting in shallower crustal levels (Sartini-Rideout et al. 2006).

In Payer-Land (74°28'N-74°47'N) (Figure 2) McClelland and Gilotti (2003) have argued that exhumation of HP granulites are connected to extensional collapse late in the collisional history of the Caledonian orogeny. This event has been dated by McClelland and Gilotti (2003) to be roughly 405 Ma. These granulites are located beneath the Payer Land Detachment Fault, occurring in paragneisses which are correlated to the Mezoproterozoic Krummedal sequence, though they do not exhibit extensive lower-P migmatitization (Gilotti and Elvevold 2002, McClelland and Gilotti 2003 and references therein), nor host any of the S-type granites. McClelland and Gilotti (2003) argues that exhumation of the deepest structural levels (e.g., Payer Land) occurred during a second extensional phase after granulite metamorphism of the structurally lowest plate at c. 405 Ma.

UHP-metamorphism have also been reported from Liverpool Land by Hartz et al. (2005), with peak metamorphism at pressure >25 Kbar and at c. 800° C, they have been dated to c. 397-393 Ma. The geology of Liverpool Land will be discussed more extensively later in this thesis (Chapter 3).

Metasedimentary rocks have also been found in northern Liverpool Land, possibly correlated with the Krummedal Sequence (Higgins 1988), and may thus indicate that Liverpool Land belongs to the same structural level as Niggli-Hagar Thrust Sheet, and should be included in the allochthon.

2.3.2 The Krummedal Sequence

The Krummedal Sequence is a Mezoproterozoic metasedimentary sequence deposited after 1100-1000 Ma (Kalsbeek et al. 2000 and references therein), which consists of medium- to high-grade mica schist's, paragneisses and quartzites. This sequence was first recognized in the Scoresby Sund region at c. 70°N by Henriksen and Higgins (1969), where it rests unconformably on the crystalline basement several places (Higgins et al. 1981, Andresen et al. 1998). The depositional contact against the underlying gneisses is generally strongly tectonized but locally original depositional relationships have been described by Andresen et al. (1998), Higgins et al. (1981) and Kalsbeek et al. (2000). Geochronological studies in the Scoresby Sund region have demonstrated that the Krummedal sequence is polymetamorphic and contain evidence of both Grenvillian (c. 940Ma) (Kalsbeek et al. 2000) and Caledonian (c. 500 - 400 Ma) events (Watt et al. 2000 and references therein).

The metamorphic grade in the Krummedal sequence varies from staurolite and kyanite bearing amphibolite (Higgins 1974), via upper amphibolite with locally abundant cordierite (Watt et al. 2000), to granulite facies metamorphism, which is characterized by migmatization containing garnetiferous neosomes (Leslie and Nutman 2003). In some places (e.g. southwestern Renland) retrogression to amphibolite facies has occurred at a variety of structural levels within the granulite (Leslie and Nutman 2003).

The Krummedal Sequence have been correlated with other Mezoproterozoic units, and supposedly occurs up to at least 76°N (Kalsbeek et al. 2000).

In Renland augen granites are interpreted by Higgins et al. (2004) to post-date a phase of regional-scale isoclinal folding and upper amphibolite-facies metamorphism. These granites have been dated to between 900-950 Ma (Kalsbeek et al. 2000, Watt et al. 2000, Leslie and Nutman 2003), which led Leslie and Nutman (2003) to interpret this as evidence for an Early Neoproterozoic event. However a gradually higher metamorphic grade from Eleonore Bay Supergroup to the upper Krummedal reported by Andresen et al. (1998) and Higgins et al. (2004) in the Petermann Bjerg and in the Fjord Region, argue against an extensive Early Neoproterozoic orogenic event (Andresen et al. 2007). Where the contact between the Krummedal Sequence and the Eleonore Bay Supergroup is not an extensional fault, it is reported to either be a gradational contact (Andresen et al. 1998) (e.g. at Kap Hedlund), or a bedding-parallel detachment, interpreted by Higgins et al. (2004) to be a modified unconformity. Both of these scenarios also speak against a large scale “Grenvillian” orogenic event (Augland 2007).

Many authors, however, have documented extensive Caledonian metamorphism and magmatism within the Krummedal Sequence (Watt et al. 2000, Hartz et al. 2001, Kalsbeek et al. 2001b., White et al. 2002, Leslie and Nutman 2003, Higgins et al. 2004, Andresen et al. 2007). This Caledonian metamorphism overprints c. 930 Ma old granites (Kalsbeek et al. 2001a.) and the metamorphic growth of monazite and overgrowth of zircon from the Krummedal Sequences is typically in the area of c. 430-420 Ma (Andresen et al. 1998, Watt et al. 2000, White et al. 2002, Leslie and Nutman 2003, Andresen et al. 2007). Granites occur from small cm scale veins and up to sheets several hundred meters thick (Kalsbeek et al. 2001a., Kalsbeek et al. 2001b.). Most of these granitoids are two-mica leucogranites, and because of the field relationship, as mention above, age distribution in the inherited zircons, geochemical signatures and the absence of Caledonian intrusions in the underlying basement, the origin is thought to be anatexis of the Krummedal Sequence (Hartz et al. 2000, Watt et al. 2000, Hartz et al. 2001, Kalsbeek et al. 2001a., Kalsbeek et al. 2001b., White et al. 2002, Leslie and Nutman 2003). These Caledonian granites are generally believed to have been emplaced around c. 430 - 420 Ma (Hartz et al. 2000, Watt et al. 2000, Hartz et al. 2001, Kalsbeek et al. 2001b., White et al. 2002, Leslie and Nutman 2003, Andresen et al. 2007), but

resent work have suggested a Late Ordovician to early Silurian magmatism (Augland 2007 and references therein).

Partial melting of the Krummedal Sequence and the high temperature metamorphism is interpreted to be caused by contractional deformation and continental thickening during the Scandian phase (Wenlock-Emsian) of the Caledonian orogeny (Andresen et al. 1998, McKerrow et al. 2000, Hartz et al. 2001, Strachan et al. 2001, Andresen et al. 2007). The heat required for magma production has been attributed to magmatic underplating, generated in the mantle wedge above a west-dipping subducting plate, which led to the high heat flow that caused anatexis of the Krummedal metasediments (Andresen et al. 2007). This could result in formation of diorites at the base of the crust which could then transport extra heat upwards and thus result in high-T metamorphism and formation of anatectic granites in the Krummedal Sequence (Andresen et al. 2007). Extension occurred in the upper crustal levels while at the same time as contraction occurred in the mid- to lower-crust (Andresen et al. 2007). This contraction caused the mid-to lower-crust to undergo deformation by flow which overturned folds to large scale recumbent folds (Andresen et al. 2007, Augland 2007). White and Hodges (2003) reported a clockwise P-T path for the metamorphism. An orogen-parallel and an East-West extension have been documented in the East Greenland Caledonides (Hartz et al. 2001, White et al. 2002). Near-isothermal decompression led to the generation of late undeformed leucogranites, mainly caused by tectonic denudation along major detachments (Watt et al. 2000, White et al. 2002, White and Hodges 2003, Augland 2007 and references therein). A similar P-T path, have been reported by Jones and Strachan (2000) in the Smallfjord Sequence further north.

2.3.3 The Eleonore Bay Supergroup

The Eleonore Bay Supergroup (EBS) is a thick Neoproterozoic sedimentary succession, exposed (1) in the Fjord Region (c. 72° to 74°N), and (2) around Ardencape Fjord, (3) in Payer Land and (4) on Canning Land, northern Liverpool Land (Soper and Higgins 1993, Higgins et al. 2004, Augland 2007) (Figure 2). The transition between EBS and the underlying sequence is either depositional, an extensional fault or a bedding-parallel detachment (Andresen et al. 1998, Higgins et al. 2004). The EBS is an over 13 km thick sedimentary package divided into two parts, a lower part composed of c. 8 km of shallow-

marine and fluvial deposits (Caby 1972), while the upper section of EBS consists of c. 5 km of shallow marine sediments (Henriksen and Higgins 1976). The depositional environment have been suggested, to range from costal plane to outer shelf environment, with the shelf orientated N-S, and deepening towards the east (Tirsgaard and S nderholm 1997). The sedimentation has been dated by deterial zircons to be between c. 990 and c. 610 Ma (Dhuime et al. 2007).

2.3.4. The Tillite Group

The Tillite group includes two diamictite units, of Vendian age, which are c. 800 - 1000 m thick (Higgins et al. 2004). This group is conformably to unconformably overlying the EBS, in the Fjord Region north of Scoresby Sund, and has been correlated with the diamictites in the foreland windows (Moncrieff 1989, Higgins et al. 2004). Outcrops of tillites are also found in Charcot Land and G seland and are described as lateral equivalents to the Tillite Group in the Niggli-Hagar Thrust Sheet (Phillips and Friderichsen 1981, Moncrieff 1989).

These Vendian successions matches closely to that of the North-East Svalbard, and was probably deposited in a contiguous basin with a common source area (Hambrey et al. 1989, Hambrey 1989 , Nystuen et al. 2008).

2.3.5. The Kong Oscar Fjord Group

The Kong Oscar Fjord Group (KOFG) is a c. 4, 5 km thick Cambrian-Ordovician succession, which in the lower part are dominated by quartz arenites that fine upwards to glauconitic sandstones and sandy shale's. Over this, carbonates, limestone's and dolostones dominate, while the uppermost unit comprise Ordovician limestone (Smith et al. 2004). The boundary between the Tillite Group and KOFG appears, according to Smith et al. (2004), to be sharp but conformable, however it seems to be likely that, where the uppermost Tillite group unit wedges out, there is a regional hiatus and/or a low angle unconformity at the base of KOFG (Smith et al. 2004). The upper part of the group is cut by the Caledonian erosional surface

(Smith et al. 2004). The KOFG consists of nine formations, but the lower Paleozoic units observed in the parautochthonous foreland (Slottet Formation and Målebjerg Formation) at the Eleonore Sø and Målebjerg tectonic windows, reveal a different depositional context (Smith et al. 2004). There is a possible hiatus between the Slottet Formation quartzite's and the overlying Målebjerg Formation carbonates, which indicates an eastwards deepening along the Laurentian Iapetus margin (Higgins et al. 2001).

The foreland and the allochthonous Neoproterozoic-Lower Paleozoic successions of the East Greenland Caledonides have been compared to the similar aged sediments in Scotland, by Higgins et al. (2001), and the conclusion was that the autochthonous-parautochthonous foreland of the East Greenland Caledonides must have lain further inland on the passive margin, and that the allochthonous EBS must have lain further outboard (Higgins et al. 2001).

2.4 Timing of thrusting and emplacement of the Niggli-Hagar Thrust Sheet

The age of emplacement of the Niggli-Hagar Thrust Sheet on top of the Neoproterozoic low-grade deposits in Eleonore Sø and Målebjerg Windows, in the Franz Joseph Fjord area (Andresen et al. 2007) is poorly constrained. Flysch deposits (c. 428 Ma), from the hinterland towards the foreland, have been interpreted by Hurst et al. (1983) to relate to the onset of thrusting and emplacement of the thrust sheet. Also, the thrusting post dates anatexis and magma generation in the Krummedal Sequence at c. 430 - 425 Ma (Andresen et al. 2007). A minimum emplacement age has been assigned by White and Hodges (2002) to c. 357 Ma, based on a pseudotachylyte that cuts across the entire nappe stack. High grade allochthonous rocks in contact with low grade rocks, exposed in tectonic windows along the thrust belt, is an important feature regarding interpretation of the evolution of the East Greenland Caledonides (Augland 2007). The occurrence of c. 405 Ma eclogites above the Nørreland Window, containing Ordovician carbonates with conodonts with CAI 5-6, indicating a thickness of the thrust sheet of c. 12.5 km (Rasmussen and Smith 2001), suggest that the eclogitized Laurentian margin had been thinned and partly exhumed after c. 390 Ma (Gilotti et al. 2004). $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age of 399 Ma from a cleaved sandstone west of Dove Bugt, is thought to date closely the time of folding, cleavage development and local thrusting (Dallmeyer et al.

1994). Andresen et al. (2007) suggest that, since these $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages are sampled from only 300-400 km north of the thrust front in André Land, they may approximate the time of thrusting of the Niggli-Hagar Thrust Sheet. A minimum displacement of c. 100 km is given by the appearance of the Niggli-Hagar Thrust Sheet in both the easternmost tectonic window and the westernmost outcrop (Andresen et al. 2007).

A west dipping reflector, in the lower crust of the Fjord Region, has been identified by Schlindwein and Jokat (2000), interpreted to represent late extensional Caledonian structures at the surface, which may represent a relic of Baltican crust or a lower crustal shear zone.

2.5 Devonian deposits

Larsen and Bengaard (1991) concluded that formation of the Devonian basin in East Greenland was caused by extensional dip-slip faulting and sinistral wrench faulting, related to the extensional collapse of the overthickened Caledonian crustal welt. The Mid-Devonian Old Red Sandstones that were deposited in the basin, was controlled by the orogen parallel extension and east-west folding (Hartz 2000). K-Ar cooling ages suggest that the faulting coincides with the deposition in Mid Devonian times (c. 385 Ma) (Larsen and Bengaard 1991).

The indications from Andresen et al. (2007) that the Niggli-Hagar Thrust Sheet, was emplaced in Mid-Devonian, and the hiatus (c. 20 Ma) between the EBS and the Old Red Sandstone deposits, points to a ‘piggy-back’ setting, in which previously deposited sediments were uplifted, eroded and redeposited.

3 Geology of Liverpool Land

3.1 Introduction

This study have been carried out in Liverpool Land, East Greenland, an area that was first thoroughly mapped in the summers of 1969 and 1971 as a part of the Geological Survey of Greenland (GGU) programme in central East Greenland (Coe and Cheeney 1972, Coe 1975). Previous work in Liverpool Land are of variable quality, but some of the first important contributions was Kranck`s general survey from 1935 (Kranck 1935), and later also Coe (1975) and Coe and Cheeney (1972). Newer contributions have been made by Hartz (2005) and Augland (2007).

Liverpool Land is situated between c. 70°30'N and 71°35'N on the east coast of Greenland, and is composed of a strongly deformed crystalline basement, with gneisses, marbles and other metasedimentary rocks, and several large granitoid intrusions of Caledonian age (Hansen and Steiger 1971, Coe and Cheeney 1972, Coe 1975). Both the gneisses and Caledonian intrusives are intruded by a dike-swarm of Permian lamprophyres. Unconformably overlying these Caledonian gneisses and intrusives is a sequence of Late Paleozoic, and Mesozoic sediments which can be traced into the Jameson Land Basin. Tertiary lamprophyres and basaltic dykes intrude the post-Caledonian sediments (Coe and Cheeney 1972).

Kranck (1935) described the southern Liverpool Land to be consisting of entirely migmatitic gneisses, penetrated by a numerous cross-cutting dikes, containing amphibolite and eclogite lenses which terminates just south of Gubbedal (Figure 5). Coe and Cheneey (1972) reinterpreted this gneiss as a veined garnet-hornblende-biotite gneiss with a N-S trending lineation. They also interpreted the amphibolite and eclogite inclusions, from Kranck (1935) as garnet pyroxenites and almost pure garnet rocks. Coe and Cheeney (1972) subdivided the metamorphic rocks, of southern Liverpool Land, into granodioritic gneisses, metasedimentary groups, veined garnet-hornblende-biotite gneiss and metasedimentary hornblende gneiss, in descending structural order. The foliation, in these gneisses, has a generally low dip which is northwards. This leads to an outcrop of the lowest structural group far to the south (Coe and Cheeney 1972, Henriksen and Higgins 1976). The three lowest groups are interpreted to be largely derived from metasediments, while the highest is the granodioritic gneiss, which

locally splits the metasedimentary gneisses (Henriksen and Higgins 1976). Coe and Cheeney (1972) also reported dunite and peridotite inclusions north of Kap Hope (Figure 5).

Recent mapping by Augland (2007) has shown that the Caledonian rocks in southern Liverpool Land can be divided into two structural different terrans, separated by the Gubbedal Shear Zone and the Gubbedal Extensional Detachment Fault. The footwall of the Gubbedal Shear Zone includes the migmatitic gneisses with eclogite- and amphibolite- lenses, while the hanging wall is dominated by undeformed Caledonian intrusives (Augland 2007).

It is generally believed that the subduction of Baltica under Laurentia, under continent-continent collision, led to HP- and UHP- metamorphism in the Baltican crust, which there resides in the Parautochthonous basement (e.g. Gee et al. 1985, Tucker et al. 2004). Since the East Greenland UHP-metamorphism appears in the overriding plate, and geophysical data from Schlindwein and Jokat (2000) suggest that the eclogite provinces of East Greenland (e.g. NEGEP and south Liverpool Land) have had a different crustal evolution than the rest of other parts of the East Greenland Caledonides, it has been suggested a more complex history for these rocks. They are hereby treated as a different terrane. The footwall of the Gubbedal Shear Zones consists of a high grade metamorphic eclogite terrain, named Liverpool Land Eclogite Province (LLEP), while the hanging wall contains Laurentian intrusives, thought to be a part of the Niggli-Hagar Thrust Sheet. A more throughoutly description of these terranes follows below.

3.2 Niggli-Hagar Thrust Sheet in Liverpool Land

The Caledonian rocks in East central Liverpool Land are by Coe and Cheeney (1972) divided into two, by a N – NW- dipping thrust. A sequence of coarsely banded gneisses forms a domal structure, centered on Kap Greg, in the hanging wall, reported to be up to 2500 m thick (Coe and Cheeney 1972, Henriksen and Higgins 1976). To the S-SE, in the footwall, more migmatitic gneisses are found (Figure 5). This thrust seems to be continuing towards the west, where it separates two igneous suites, the Hodal-Storefjord Monzodiorite and the Hurry Inlet Granite. In the foot wall, west central Liverpool Land, a more dioritic intrusion containing garnet is found, this is most likely derived from Krummedal (Johnston et al. 2008).

Rocks in north Liverpool Land, is dominated by hornblende-biotite gneisses, migmatitic gneisses and a thick metasedimentary group. The gneisses contain inclusions of marble, amphibolite and banded quartzite's (Coe and Cheeney 1972, Henriksen and Higgins 1976)

North of the eclogite terran, in south Liverpool Land (Figure 5), rocks are dominantly plutonic, including the seven groups, described by (Coe and Cheeney 1972). Of these the Hurry Inlet Granite is by far the largest (Coe and Cheeney 1972, Coe 1975). Rb-Sr age for the Hurry Inlet Granite, by Hansen and Steiger (1971), are 434 ± 10 Ma, while Gleadow and Brooks (1979) reported a fission track age from titanite of 413 ± 10 with a retention temperature of $c. 250 \pm 50$ °C. Recent investigations by Augland (2007) points to a two phase emplacement of the Hurry Inlet Batholite, with the older phase being 445 ± 4 Ma and the younger 438 ± 4 Ma, by ID-TIMS U-Pb dating. A crystallizing age for the Hodal-Storefjord Monzodiorite of 423 ± 7 Ma, by ID-TIMS U-Pb dating, is also given by Augland (2007).

Lamprophyres that cuts the granitoids in Liverpool Land, are younger than lamprophyres in the Fjord Region, and are given a preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ age of 262 - 260 Ma (unpublished data) (Figure 4), based on large biotite/phlogopite phenocrystals. They have an approximately north-south direction, and are usually $c. 1$ m in width. Sampling of the lamprophyres on Liverpool Land was done in the summer of 2008, for paleomagnetism, geochemistry and further $^{40}\text{Ar}/^{39}\text{Ar}$ dating.



Figure 4: A lamprophyre dyke, c. 1 m wide, striking approximately north-south (c. 327°) cutting the Hodal-Storefjord Monzodiorite, Liverpool Land.

An isolated outlier of Upper Paleozoic and Mesozoic sedimentary rocks appears on the southernmost part, as well as along the Hurry Inlet, western Liverpool Land (Figure 5). The Upper Paleozoic sedimentary rocks are unmetamorphosed, mostly coarse grained clastics. Coe and Cheeney (1972) subdivided the sedimentary cover rocks in southern Liverpool Land into two groups, the upper containing sand- and silt-stones, whereas the lower contains conglomerates. A fault separates these two groups and the conglomerates are thought to be older. Both these lithologies dip to the west, the conglomerates with a lower angle than the upper group. There are also some calcareous bands (Coe and Cheeney 1972). The Mesozoic rocks contain Triassic sandstones, which crops out at the head of Hurry Inlet and in Kiltal. In the northernmost part of this sandstone, there is a marked unconformity between the sandstones and the crystalline basement. They dip gently to the west (Coe and Cheeney 1972). Coe and Cheeney (1972) also reported a poorly exposed Triassic-Jurassic rock, north-east of Kap Hope.

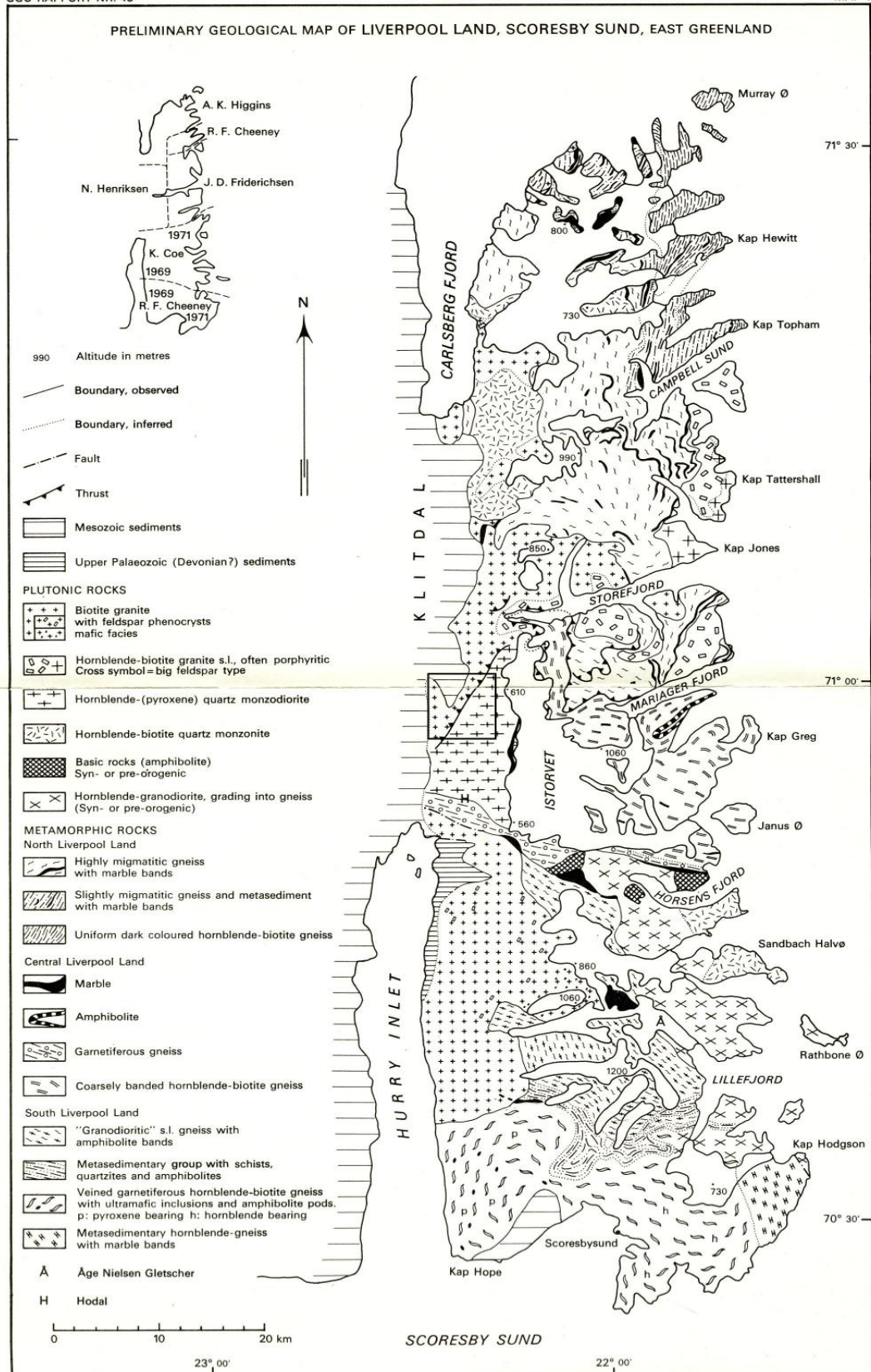


Figure 5: A detailed map of Liverpool Land from Coe and Cheeney (1972). The black box marks the sample area for this thesis. The black box marks the study area.

Host rocks for the Hurry Inlet Granite are reported to be an assemblage of more or less stratified gneiss, and migmatitic granodiorite gneiss in which amphibole is conspicuous (Coe 1975). To the north it borders to a siliceous garnet gneiss, overlain by marble and amphibolites (Coe 1975). A petrographic comparison with rocks of similar lithologies, near and far from the contact to the granite, shows there have been minimal effect of contact metamorphism, and mostly restricted to retrogression (Coe 1975).

3.3 Liverpool Land Eclogite Province.

The Liverpool Land Eclogite Province (LLEP) makes up the southern part of Liverpool Land (Figure 5), and is dominated by a relative homogeneous migmatitic gneiss with lenses of eclogite, metaeclogite, amphibolite and garnet-amphibolite (Augland 2007). These eclogites have a preliminary reported age for the UHP-metamorphism of c. 397 - 393 Ma and a peak at c. 800 °C and > 25 Kbar (Hartz et al. 2005). Newer U-Pb ages for the eclogites are given in Augland (2007) to be 399 ± 2 Ma. This eclogite terrain is suggested to be a part of the Baltican plate (Hartz et al. 2005, Augland 2007), and part of the exhumation of this terrain was achieved by extensional displacement of the Gubbedal Extensional Detachment Fault.

3.4 Purpose of study

This study focuses on the nature of the postulated thrust separating the Hodal-Storefjord Monzodiorite from the granitoids to the north (Figure 5), and geochemistry of the Hodal-Storefjord intrusives. To test if one of the mafic enclaves in the Hodal-Storefjord Monzodiorite, previously dated to 425 Ma, could represent remnants of an older (Ordovician?) magmatic event, a U-Pb study was also carried out. Since granitic rocks from Liverpool Land appears to be different from the normal two-mica granitoids found most places in the East Greenland Caledonides, derived from the Krummedal metasedimentary sequence, it has been suggested that they are connected to the similar granitoids found in Milne Land (Augland 2007, Kalsbeek et al. 2008). If the geochemical signatures are similar enough possibilities of using Isotope studies from Milne Land granitoids may be useful for interpreting the tectonic setting for the granitic intrusions, and whether there is a mantle or a continental signature.

It has been argued that Liverpool Land is a continuation of the Uppermost Allochthon described from the Norwegian Caledonides by Roberts and Gee (1985). In this study I will look for evidence for this argument. Especially by looking at the Helgeland nappe, to see if there is a possible correlation between the Liverpool Land tectonic setting and the arc setting suggested for the Helgeland Nappe Complex (Barnes et al. 2007). A possible link to the Scottish Caledonides has also been proposed (Augland 2007, Kalsbeek et al. 2008).

4 Geology of sampled area

4.1 Introduction

The area around our main camp (70°59.117'N, 022°22.380'W), is in the hanging wall of the Gubbedalen Shear Zone, comprising the Hurry Inlet Granite, the Hodal-Storefjord Monzodiorite, lamprophyres and dolorite dykes, and quartzite's. The area was dominated by a late extensional fault zone, which divides the granites from the monzodiorites (Figure 6 and Figure 8). The granites were situated in the west/north-west and the monzodiorites in the south-east/east of the fault zone. In the monzodiorites there were mafic enclaves and possible mafic xenoliths in larger occurrences (Figure 7). Near the fault zone both the Hurry Inlet Granite and the Hodal-Storefjord Monzodiorite are migmatized, and contain mafic enclaves or mafic xenoliths. At the fault zone quartzitic bodies were also present (Figure 9). The melt that intrudes the migmatite is coarser grained than the granitoids that surround it, but of approximately the same composition. Further west the Hurry Inlet Granite contains migmatite with less mafic enclaves and has a clear compositional banding. Lamprophyre dykes, striking approximately north, cut through both the igneous suites and the fault zone.

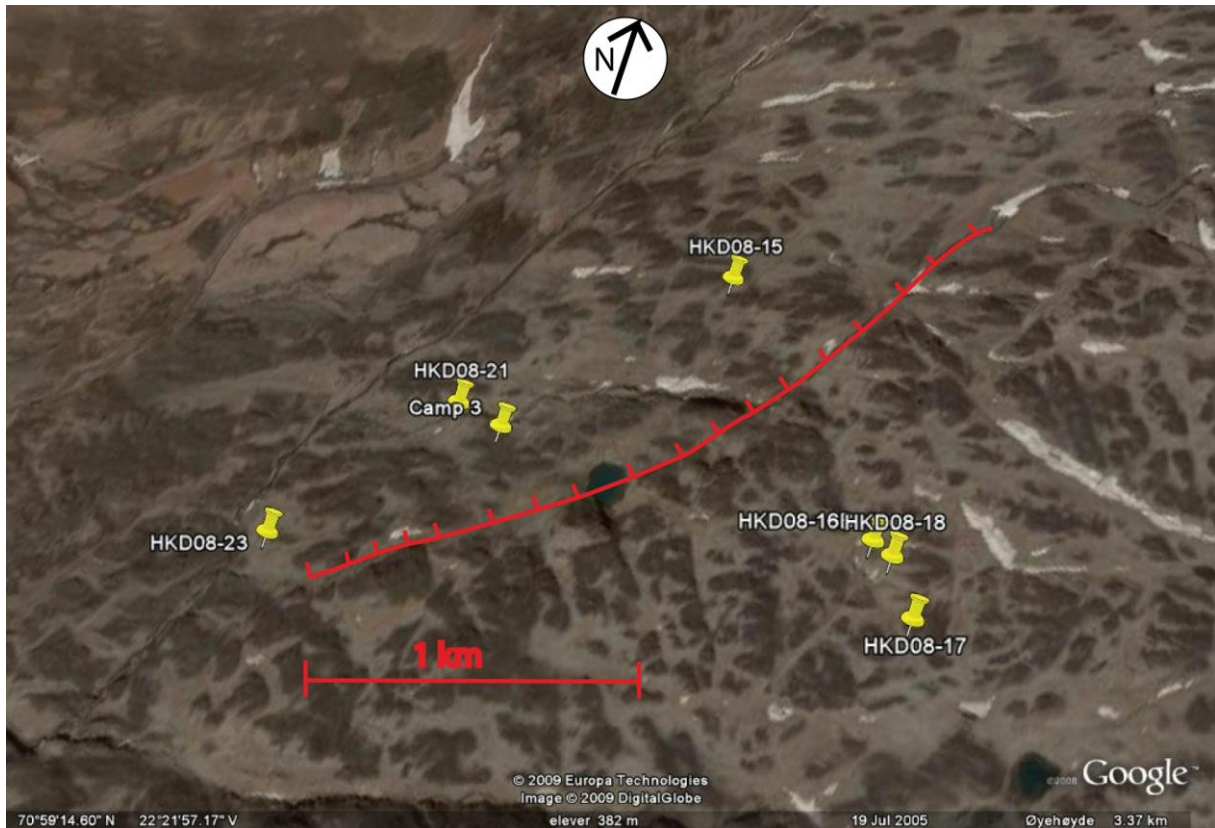


Figure 6: A Google Earth satellite image of the study area at Liverpool Land. The pins show the samples taken. The west of the fault line, marked red is from the granite and on the east/south-east side the monzodiorite. HKD08-18 and HKD08-23 are a mafic enclave and a mafic enclave possible xenolith, respectively. Three of the samples are taken from an area further south, while two are from further east.



Figure 7: Migmatite with mafic enclaves cut by more granitic material. This is taken from near the main camp (Figure 6).

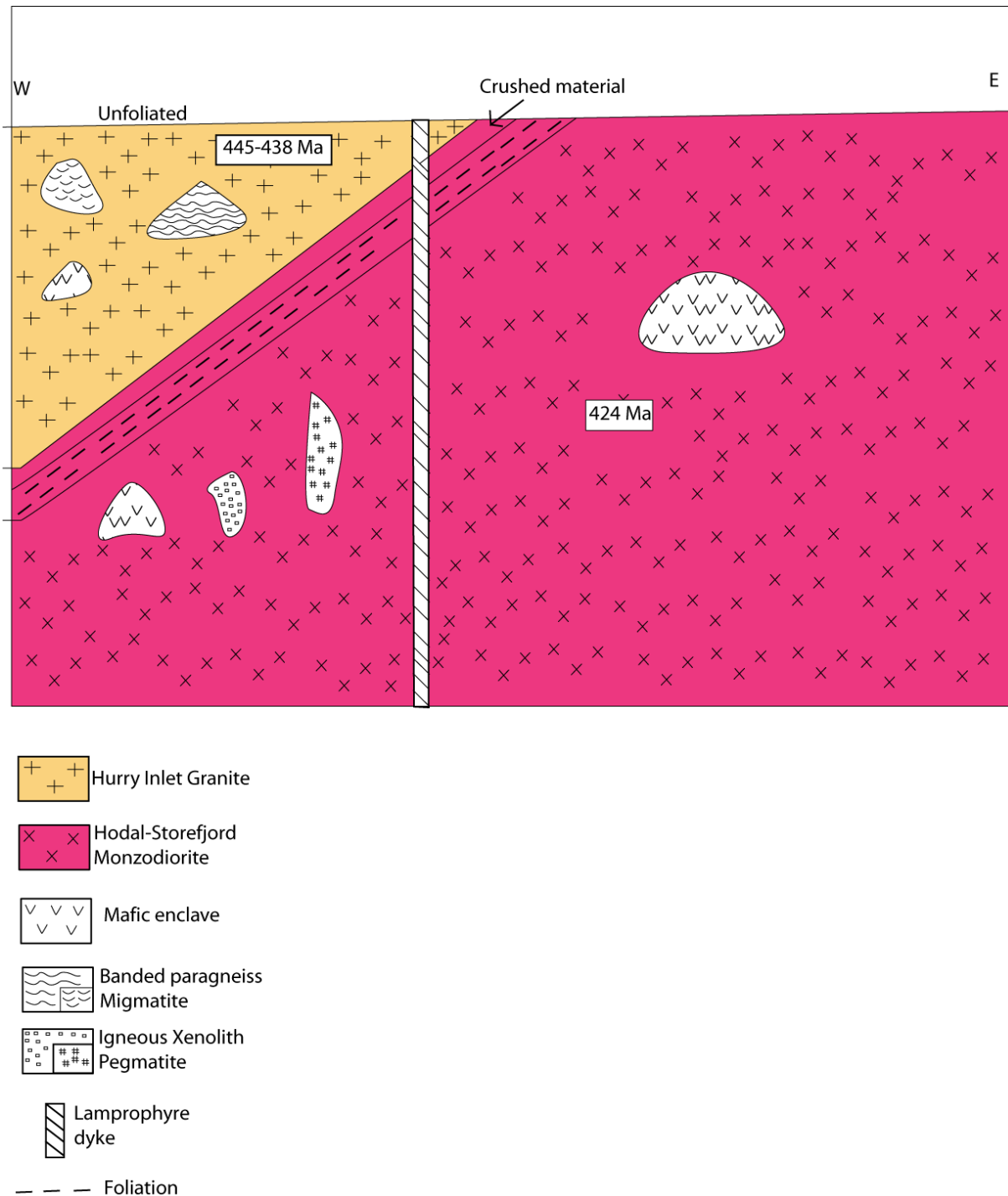


Figure 8: Schematic profile across the NE-faultzone, illustrating the relationship between the various units described in the text. ID-TIMS U/Pb ages for the intrusives are from Augland (2007).

The reason for choosing this area as the study area, was the presence of an apparent thrust on the map from Coe and Cheeney (1972), but this was not the case as this “thrust” was a late extensional fault, and also if there were traces of older magmatism ($> c. 425$ Ma) in the intrusives, as is the case in the Uppermost Allochthon in the Norwegian Caledonides (e.g. Barnes et al. 2007). Since this was a late extensional fault, the focus was then put on the

geochemistry and tectonical setting of the igneous suites, especially the Hodal-Storefjord Monzodiorite, and age of one mafic enclave (HKD08-23), to document possible older source for the enclaves, assimilation and/or magma mingling.



Figure 9: Quartzitic bodies at the fault zone. Possible derived from the Krummedal Sequence. The quartzite bodies have a thickness of c. 1 m.

4.2 Main rock units

Petrography of the rocks is done under a petrographic microscope on thin sections, made of 11 samples from Liverpool Land intrusives. They are given petrographic names based on Streckeisen (1967) classification diagrams.

4.2.1 Introduction

Our main camp was located on Liverpool Land at 70°59.117'N and 022°22.380'W, and the samples was collected from sites around the camp, two from further north-east and three a bit south of the main area (Table 1) (Figure 6).

Sample id:	Coordinates		Thin section	Petrographic name	XRF	ID-TIMS
HKD08-01	N70°52.628`	W022°18.708´	Yes	Monzodiorite	Yes	No
HKD08-02	N70°52.684`	W022°16.813´	Yes	Monzodiorite	Yes	No
HKD08-03	N70°52.656`	W022°18.410´	Yes	Monzodiorite	Yes	No
HKD08-08	N71°14.524`	W022°13.366´	Yes	Monzodiorite	Yes	No
HKD08-09	N71°14.524`	W022°13.366´	Yes	Granite	Yes	No
HKD08-15	N70°59.512`	W022°21.766´	Yes	Granite	Yes	No
HKD08-16B	N70°59.243`	W022°20.585´	Yes	Monzodiorite	Yes	No
HKD08-17	N70°59.168`	W022°20.271´	Yes	Monzodiorite	Yes	No
HKD08-18	N70°59.236`	W022°20.477´	Yes	Mafic enclave	Yes	No
HKD08-21	N70°59.117`	W022°22.624´	Yes	Granite	Yes	No
HKD08-23	N70°58.790`	W022°23.089´	Yes	Mafic enclave/xenolite	Yes	Yes

Table 1: This table shows the coordinates and analyses done to the different samples.

As shown in Table 1, the samples are from four different suites; monzodiorite, granite, one mafic enclave and one possible mafic xenolith.

Samples HKD08-01, HKD08-02 and HKD08-03 (Figure 10, 11 and 12 respectively) are collected from a site further south than the bulk of samples, in a glacier valley, and they are samples of a monzodiorite. Around HKD08-01 a late fluid phase pegmatite was observed, which cross cuts an earlier melt. The sample was taken in an area without this phase, and was quite clean. HKD08-02 was more fine grained, and was taken near the glacier river, while the HKD08-03 was more similar to the HKD08-01, as it was taken not far from it.



Figure 10: A picture of medium grained monzodiorite (HKD08-01) in which there has been a reaction with a late fluid phase pegmatite cross-cutting the earlier monzodiorite.



Figure 11: A picture of a fine-grained monzodiorite, where the sample HKD08-02 was taken. This sample is more fine-grained than the other monzodiorites, and contains almost no mafic minerals.



Figure 12: Monzodiorite outcrop near the HKD08-01. The sample HKD08-03 was taken here.

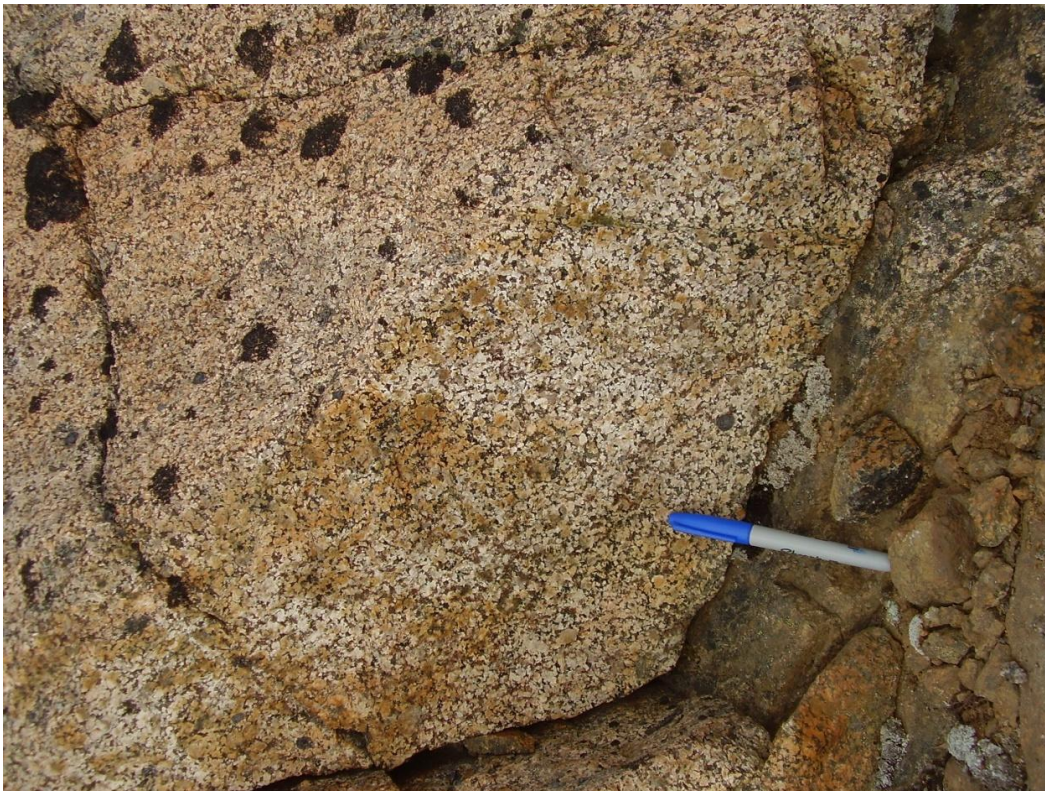


Figure 13: A medium grained monzodiorite (HKD08-16B). Pen for scale, c. 15 cm.

HKD08-08 and HKD08-09 were collected from an outcrop further north of the main camp (see above), and the HKD08-09 is from a granite body that crosscuts the monzodiorite of HKD08-08. Because we collected these two using a helicopter, time and money didn't allow me to take pictures or describe the surroundings to a further extent.

The rest of the samples HKD08-15, HKD08-16B (Figure 13), HKD08-17 (Figure 14), HKD08-18 (Figure 15), HKD08-21 (Figure 16) and HKD08-23 (Figure 17) were collected in the area of the main camp (Figure 6).

HKD08-15 and HKD08-21 are granites from two different outcrops. HKD08-15 was taken from an outcrop of frost wedged granite but clearly *in situ*, whereas HKD08-21 was taken from a granitic body with large plagioclase phenocrysts at the end of a pegmatite dyke (Figure 18). HKD08-17 and HKD08-16B are quite similar looking monzodiorites, taken from a site near each other. HKD08-18 is a sample from a large mafic body, which resides in the monzodiorite pluton. This body contains several felsic lenses of up to 15 cm. in diameter.

The HKD08-23 was taken from a mafic intrusion in the granite, which based on field evidence, seemed to predate the migmatite. It was therefore suggested it was a mafic xenolith.



Figure 14: A medium grained monzodiorite (HKD08-17), similar to the other monzodiorites. Pencil length c. 20 cm.



Figure 15: HKD08-18 is a mafic body inside the monzodiorite. This body has inclusions of granitic material (see picture). Pencil length c. 20 cm.



Figure 16: A picture of a granite with large plagioclase phenocrysts (HKD08-21). Camera is c. 10 cm in length.

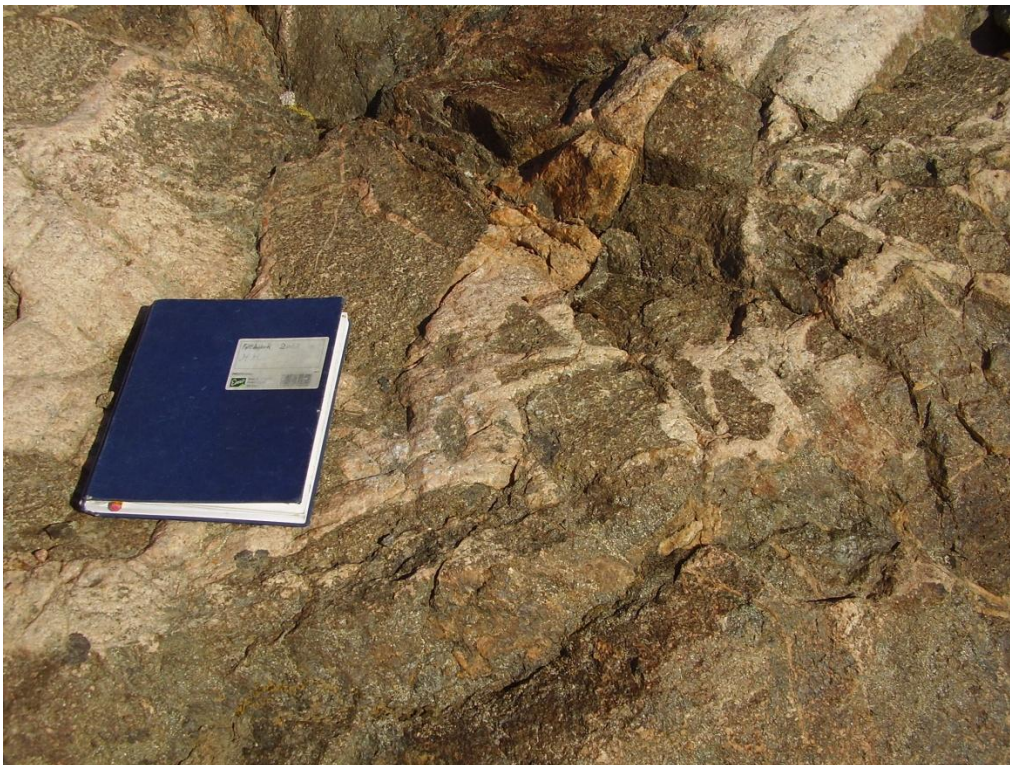


Figure 17: Here you can see granitic material intruding a more mafic material, this is either a mafic enclave or possible a xenolith. The HKD08-23 is taken from this location.

4.2.2 Hurry Inlet Granite

The granite sampled from c. 70°59.500`N, on Liverpool Land, is comparable to the Hurry Inlet Granite described by Coe (1975). Evidence suggest that the Hurry Inlet Granite was emplaced to high crustal levels in Lower Paleozoic times (Coe 1975). U/Pb ages from zircon from Augland (2007) suggest two different phases of emplacement. The older phase at c. 445 Ma and the younger at c. 438 Ma. This batholith covers an area of c. 400 km², and is the largest granitic mass on Liverpool Land (Coe 1975).

In the sample area the Hurry Inlet Granite appears at the N-W side of the fault zone (Figure 6). Near the fault zone the granite contains blobs of migmatite and mafic enclaves. Dykes of pegmatite are also observed here which is in sharp contact with the granite (Figure 18). Banded paragneiss is also present here. The granite appears unfoliated with large plagioclase phenocrysts in many outcrops.



Figure 18: To the right a pegmatitic dyke, which is in sharp contact with the granite (left). A compass for scale c. 10 cm long.

Geochemical signatures and petrological evidence suggest that the Hurry Inlet Granite batholith is related to arc-magmatism, represented by the older granites in Renland (Augland 2007).

The three granite samples are quite different from each other in modal composition (Table 2). HKD08-09A is very leucocratic, and contains only a small amount of dark minerals (hematite < 5 %) and medium to coarse grained, while HKD08-15 is quite homogenous fine to medium grained and appears reddish brown. The HKD08-21 is also fine to medium grained, but it contains large phenocrysts of plagioclase, up 2 cm in diameter. It's appearance is dark red to black.

The granites varies in modal quartz from c. 15-40 %, and two of the samples, HKD08-15 and HKD08-21, contains chlorite and small amounts of mica, while HKD08-09A just have trace amounts of muscovite. The composition of HKD08-09A is different than the other two, in modal composition, with mostly K-feldspar and a fair amount of hematite. The other two are more similar in composition. It can be that HKD08-09A are from a different pluton or from a different phase of the Hurry Inlet Batholite (Augland 2007), it was also taken from a granite farther north-east than the other two.

	HKD08-09A	HKD08-15	HKD08-21
Plagioclase:	5 %	50 %	40 %
Mikrocline:	75 %		
Quartz:	15 %	40 %	35 %
Amphibole:			
Biotite:			
Muskovite:	< 1 %	<5 %	
Zircon:			<1 %
Chlorite:		5 %	c.20 %
Titanite:			5 %
Hematite:	< 5 %		<1 %

Table 2: A table of the modal composition of the granite samples.

4.2.3 Hodal-Storefjord Monzodiorite

This rock was named the Hodal-Storefjord quartz monzodiorite by Coe and Cheeney (1972) based on its location and the range of quartz content of 5-15 %. The emplacement of this pluton is dated to c. 424 Ma, and it covers an area of more than 50 km² (Augland 2007).

The monzodiorite appears on the S-E side of the fault zone. Towards the fault zone there is a steep foliation towards the granite. Igneous xenolith and pegmatite as well as mafic enclaves are present in the monzodiorite. The monzodiorite in the sample area appears quite homogenous. At 70°59.260'N, 022°21.129'W we observed a mylonitic foliation with a strike of c. 184° and a dip of c. 47°. The transition from the monzodiorite and the mylonite is a gradual transition. Close to this we also observed what looked like a pseudotachelyte, which was cutting the foliation (Figure 19).



Figure 19: A small pseudotachelyte vein in mylonite footwall and suggest an uplift of the footwall compared to the hanging wall, and thus extension (N 70°59.245', W 022°21.063'). The tip of the pencil is c. 1 cm.

The Hodal-Storefjord is also comparable to granitoids in Renland, the younger generations, based on age overlap and petrography (i.e. amphibole, low modal quartz and occurring orthopyroxene) (Augland 2007).

The monzodiorite samples are medium to coarse grained and quite homogenous in appearance. One of the samples, HKD08-02, have a different modal composition than the other samples (Table 3). It does not contain any amphibole. HKD08-02 was taken near HKD08-01 and HKD08-03, but had a different appearance, and was more fined grained.

HKD08-08 was taken from an area further north-east and is quite similar in modal composition to the other samples, except a large amount of mica, both biotite and muscovite, and could thus have come from a different pluton or a different phase.

The other samples are more similar in composition. They all contain a fair amount of amphibole and high amounts of feldspars, mostly plagioclase (Table 3). These samples contain more amphibole than those reported from Augland (2007).

	HKD08-01	HKD08-02	HKD08-03	HKD08-08	HKD08-16B	HKD08-17
Plagioclase:	60 %	70 %	c. 70 %	C. 60 %	75 %	75 %
Microcline:		c. 25%	1 %	5 %		
Quartz:	10-15%		10 %	5 %	10 %	5 %
Amphibole:	20 %		5 %	10 %	15 %	15 %
Biotite:	c. 5 %	5 %	10 %	15 %		
Muscovite:	c. 5 %		< 1 %	5 %	< 1 %	< 1 %
Hematite:			5 %			5 %
Other:			< 5 %	< 2 %		

Table 3: This table shows the modal composition of the monzodiorites.

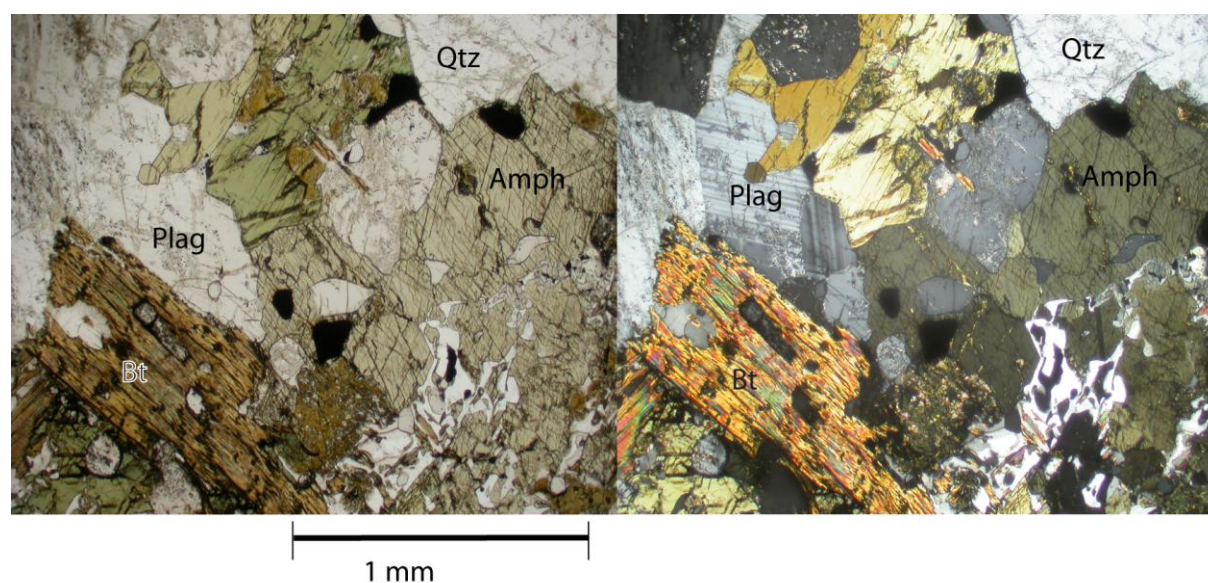


Figure 20: Photomicrograph of on sample of the Hodal-Storefjord Monzodiorite (HKD08-03). The left is with normal light, while the right is taken with crossed nichols.

4.2.4 Sedimentary rocks

Sedimentary rocks of Upper Paleozoic and Mesozoic age are found at Liverpool Land (Coe and Cheeney 1972). The Paleozoic rocks are divided into two lithological groups (1) the lower conglomerates and (2) the upper sand- and silt-stones. These are again overlain by Mesozoic sandstones and marls (Coe and Cheeney 1972).

4.2.5 Mafic xenoliths and enclaves

Mafic enclaves and possible mafic xenoliths are found in both the monzodiorite and the granite. They occur both as small lenses and as larger bodies, and often with intrusion of granitic material. In this thesis I have sampled two such enclaves. Their modal composition are given in Table 4.

The HKD08-18 has a dark fine-medium grained matrix and some larger grains that are red/pink in appearance. It contains almost exclusively mafic minerals, except for a small amount of plagioclase (~ 8 %).

The HKD08-23 is medium grained and appears dark-grey. It has an equal content of biotite, muscovite, amphibole and plagioclase and appears to be quite homogenous (Table 4). The presence of this kind of enclaves or xenoliths in the granitic rock is a clear sign of magma mingling, meaning that the individual chemical compositions are still present and quite clear (Lai et al. 2008). One can clearly see the difference between the granitic material and the mafic material on Figure 17.

	HKD08-18	HKD08-23
Amphibole:	80 %	25 %
Olivin:	2 %	
Feldspar:	8 %	25 %
Hematite:	10 %	< 1 %
Biotite:		25 %
Muskovite:		25 %

Table 4: Table showing the modal composition of the mafic enclave (HKD08-18) and the mafic enclave/xenolith (HKD08-23).

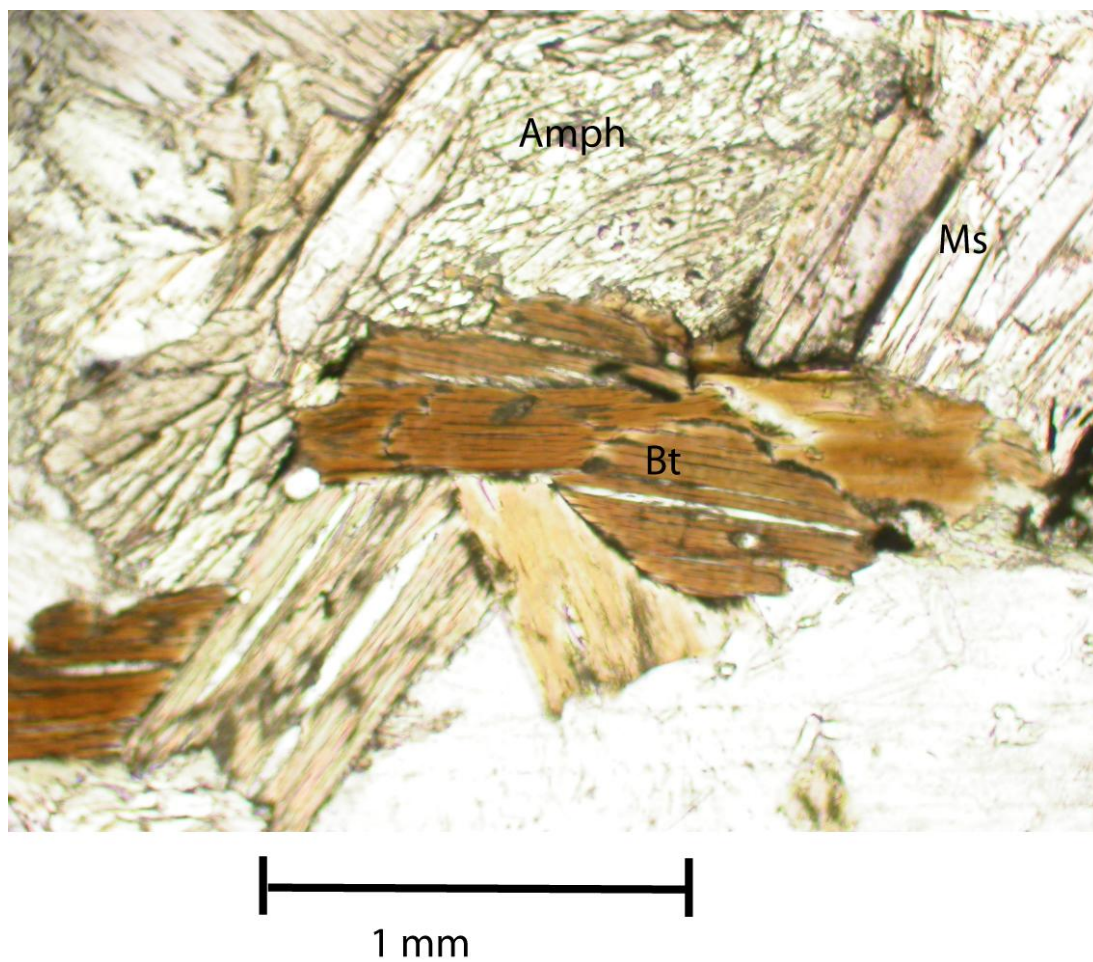


Figure 21: Photomicrograph of HKD08-23, which is the mafic enclave dated later in this paper.

5 Major and trace element geochemistry of Caledonian Intrusives

To characterize and identify the plate tectonic setting of the Caledonian intrusives in a part of Liverpool Land, 11 samples were analyzed for major and trace element composition. Zircons was also extracted from one mafic enclave/xenolith, thought to represent an older mafic xenolith in the Hodal-Storefjord Monzodiorite for ID-TIMS dating (Table 5). The results are presented below.

Sample:	Rock type:	Thin section:	Crushed:	Magnetic separation and heavy liquid:	Quarted:
HKD08-01	Monzodiorite	X	X		X
HKD08-02	Monzodiorite	X	X		X
HKD08-03	Monzodiorite	X	X		X
HKD08-08	Monzodiorite	X	X		X
HKD08-09A	Granite	X	X		X
HKD08-15	Granite	X	X		X
HKD08-16B	Monzodiorite	X	X		X
HKD08-17	Monzodiorite	X	X		X
HKD08-18	Mafic Enclave	X	X		X
HKD08-21	Granite	X	X		X
HKD08-23	Mafic Enclave/Xenolith	X	X(also Retch)	X	X

Table 5: Table summarizing the modal composition of the analyzed samples and the various analytical methods which will be used for each sample.

5.1 Analytical methods and sample description

All the samples (Table 5) where prepared for XRF. 6 of them are monzodiorites, 3 are granites, one is a mafic enclave and the last one is a possible mafic xenolith.

First of all the samples were crushed to gravel with a jaw crusher, then I quarted out c. 15-20 g of each sample and put each sample in a clean jar. This was then crushed to powder with an

agate mortar. Of this c. 3 g was taken out for main element analyses. These 3 grams was then burned to get rid of organic material, and put in an oven for 1 hour at 1000°C and then weighed to calculate the loss of ignition (LOI). Of this I measured up 0, 6 g and mixed it with c. 4.2 g $\text{Li}_2\text{B}_4\text{O}_7$ and melted in a Pt-cup then cast it into a glasbead. The analyses data was calculated back from burned to received sample.

9, 6 g of each sample was mixed with 2, 4 g of binding wax (Hoechst C) and pressed to tablets for trace element analyses.

The analyses were made on a PANalytical Axios 4 kW x-ray spectrometer. Errors are calculated from regression analysis of international standards given by: error =

$K_{\text{Element}} * \sqrt{0.1 + C_i[\%]}$, where C_i is the reported concentration in % and K_{Element} is given by Table 6 for 1σ at 68 % confidence interval. Trace elements were analyzed using the Pro Trace program and the main elements with the Hovedelement program.

Element	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	MgO	CaO	K ₂ O	Na ₂ O	MnO	P ₂ O ₅
$K_{\text{ELEMENT}} / \%^{1/2}$	0,09	0,04	0,06	0,02	0,08	0,06	0,04	0,07	0,01	0,02

Table 6: The uncertainties is given for 1σ level at 68 % confidence interval, by multiplying with 2, we get the 95 % confidence interval.

The trace element analyses are given in mg/kg (ppm) except S, F and Cl which is given in %. The lower determination limits is given by Table 7, while uncertainties is given by Table 8.

Ag	As	Ba	Cd	Ce	Co	Cr	Cu	Ga	La	Mo	Nb	Nd	Ni	Pb
10	10	10	10	20	4	4	2	1	10	1	1	10	2	3

Rb	Sb	Sc	Sn	Sr	Th	U	V	W	Y	Yb	Zn	Zr	Cl	F
1	15	5	10	1	4	2	5	5	1	5	1	1	0,05	0,1

S	Au*	Bi*	Br*	Cs*	Ge*	Hf*	Hg*	I*	Pt*	Se*	Sm*	Ta*	Te*	Tl*
0,02		10	5	10	1	5	20	100		5	10	4	10	20

Table 7: All detection limits is given by mg/kg (ppm), except S, F and Cl which is given by %.

Element	Measure area /mg/kg	Uncertainty
Co, Cr, Cu, Ga, Mo, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn	< 50 >50	< ± 10 % relative < ± 5 % relative
Ag, As, Ba, Cd, La, Nd, Sc, Sn, W, Zr	< 50 >50	< ± 20 % relative < ± 10 % relative
Ce, Ge, Hf, Mn, Sb, Sm, Ta, Yb	< 50 >50	< ± 30 % relative < ± 15 % relative
Bi, Br, Cs, Hg, I, Se, Te	< 100 >100	< ± 50 % relative < ± 25 % relative
F, Cl, S, CaO, K ₂ O, Fe ₂ O ₃ , MgO, TiO ₂	< 10000 >10000	< ± 50 % relative < ± 25 % relative
Al ₂ O ₃ , SiO ₂ , Na ₂ O, P		< ± 50 % relative

Table 8: Shows the measure area and uncertainties for the different trace-elements.

The analyses were done at NGU in Trondheim in November/December 2008.

5.2 Analytical results

Table 9 shows the results of the XRF analyses. All the main elements are shown in wt % while the trace elements are either shown as ppm (mg/kg) or as %. Errors are not given in this table.

Prove id.	Column1	HKD08-01	HKD08-02	HKD08-03	HKD08-08	HKD08-09A	HKD08-15	HKD08-16B	HKD08-17	HKD08-18	HKD08-21	HKD08-23
SiO2	[%]	54,9	70,6	54,9	62,5	72,9	69,9	55,6	55,7	43,8	65,1	51,4
Al2O3	[%]	17,4	14,7	18,3	15,8	14,0	14,5	17,5	17,2	8,76	15,9	11,7
Fe2O3	[%]	6,77	1,68	6,65	4,84	0,884	2,32	6,43	6,28	18,2	3,86	10,7
TiO2	[%]	1,15	0,243	1,15	0,887	0,078	0,474	1,10	1,07	2,86	0,731	1,05
MgO	[%]	3,46	0,487	3,25	2,23	0,118	0,683	3,29	3,24	9,00	1,44	11,7
CaO	[%]	6,32	2,30	6,94	4,29	0,342	1,06	6,09	6,34	10,5	2,17	5,43
Na2O	[%]	4,49	4,16	4,77	4,19	4,20	3,54	4,73	4,56	1,12	3,85	1,21
K2O	[%]	2,74	3,72	1,61	3,36	5,64	5,13	2,82	2,77	1,71	4,25	1,70
MnO	[%]	0,096	0,028	0,087	0,075	0,021	0,035	0,087	0,094	0,257	0,045	0,165
P2O5	[%]	0,582	0,073	0,577	0,412	0,044	0,162	0,535	0,521	1,38	0,319	0,370
Gl.tap	[%]	1,33	0,367	1,50	1,12	0,500	1,83	1,19	0,722	1,89	2,03	3,83
Sum Hoved	[%]	99,3	98,4	99,7	99,8	98,8	99,6	99,4	98,6	99,5	99,7	99,2
BaO*	[%]	0,197	0,074	0,186	0,139	<0,025	0,165	0,200	0,192	0,162	0,205	0,063
Cr2O3*	[%]	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	0,097
CuO*	[%]	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
HfO2*	[%]	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
NiO*	[%]	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	0,010	<0,01	<0,01	<0,01	0,035
PbO*	[%]	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
SrO*	[%]	0,244	0,087	0,262	0,175	<0,04	0,098	0,235	0,231	0,062	0,124	0,076
V2O5*	[%]	0,027	<0,02	0,031	<0,02	<0,02	<0,02	0,026	0,027	0,076	<0,02	0,031
ZnO*	[%]	0,013	<0,01	0,012	0,011	<0,01	<0,01	0,012	0,013	0,034	<0,01	0,015
ZrO2*	[%]	0,046	<0,02	0,045	0,045	<0,02	0,032	0,045	0,041	0,118	0,045	<0,02
Ag	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
As	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ba	[mg/kg]	1580	548	1450	967	116	1160	1520	1480	1170	1480	467
Cd	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ce	[mg/kg]	141	22	139	152	<20	104	152	149	307	136	56
Co	[mg/kg]	22,4	<4	21,6	14,4	<4	4,5	21,2	20,3	55,4	9,5	47,1
Cr	[mg/kg]	32,3	18,9	23,7	16,9	5,5	14,9	24,8	24,4	89,0	44,9	613
Cu	[mg/kg]	4,6	<2	10,5	3,0	<2	2,2	32,6	25,4	4,7	3,8	15,8
Ga	[mg/kg]	22,8	16,9	23,6	21,1	17,0	18,2	23,1	22,9	20,3	19,3	16,3
La	[mg/kg]	60	19	62	68	16	47	60	64	118	67	15
Mo	[mg/kg]	1,3	<1	<1	1,3	<1	1,2	<1	1,0	2,3	<1	1,6
Nb	[mg/kg]	7,1	3,2	5,9	11,8	6,6	9,7	6,7	6,7	20,8	10,5	7,6
Nd	[mg/kg]	73	15	73	63	13	40	71	80	159	60	30
Ni	[mg/kg]	21,6	2,9	18,3	12,5	2,1	6,6	19,9	18,9	49,9	9,5	202
Pb	[mg/kg]	32,0	60,5	29,9	45,4	86,7	64,5	32,7	35,8	37,6	53,4	46,8
Rb	[mg/kg]	43,5	107	22,1	96,1	168	157	49,2	44,5	25,6	118	82,6
Sb	[mg/kg]	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
Sc	[mg/kg]	14,3	<5	14,0	8,9	<5	6,1	13,3	14,8	38,8	7,6	23,2
Sn	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Sr	[mg/kg]	1830	518	1910	1240	114	654	1800	1750	397	919	480
Th	[mg/kg]	<4	<4	<4	22,7	8,3	15,6	4,3	<4	10,5	19,5	<4
U	[mg/kg]	4,1	<2	4,0	5,6	<2	3,6	4,5	4,1	<2	4,2	2,7
V	[mg/kg]	116	18,7	117	73,9	<5	31,7	109	103	343	52,5	130
W	[mg/kg]	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Y	[mg/kg]	22,0	5,1	20,4	21,1	19,1	20,7	21,5	21,9	54,6	24,3	27,6
Zn	[mg/kg]	98,2	27,3	95,5	81,6	25,9	48,0	94,4	89,0	274	67,8	116
Zr	[mg/kg]	263	85,6	262	256	56,7	228	272	255	691	272	32,4
Cl	[%]	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05
F	[%]	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1
S	[%]	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Bi*	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Br*	[mg/kg]	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Cs*	[mg/kg]	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ge*	[mg/kg]	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Hf*	[mg/kg]	6,6	<5	<5	8,3	<5	6,6	9,6	5,8	18,4	8,7	<5
Se*	[mg/kg]	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sm*	[mg/kg]	12	<10	<10	<10	<10	<10	12	17	20	<10	<10
Ta*	[mg/kg]	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4
Te*	[mg/kg]	16	<10	<10	<10	<10	<10	<10	<10	14	12	<10

Table 9: This table shows the analytical values for each element for the different samples.

5.3 Geological interpretation

To characterize the analyzed samples geochemically data from the XRF analyses was plotted in various classification diagrams, many of which are described in Pearce et al. (1984). Most of the diagrams are based on the trace element concentrations, because these elements usually show more of the diversities in the different rock types than the major elements. This is because trace elements are more sensitive to changes, and because of the mobility of major elements especially the alkalis. Even so, some of the major element diagrams gives us important information on the general tectonic environment of the melts (Maniar and Piccoli 1989, Winter 2001).

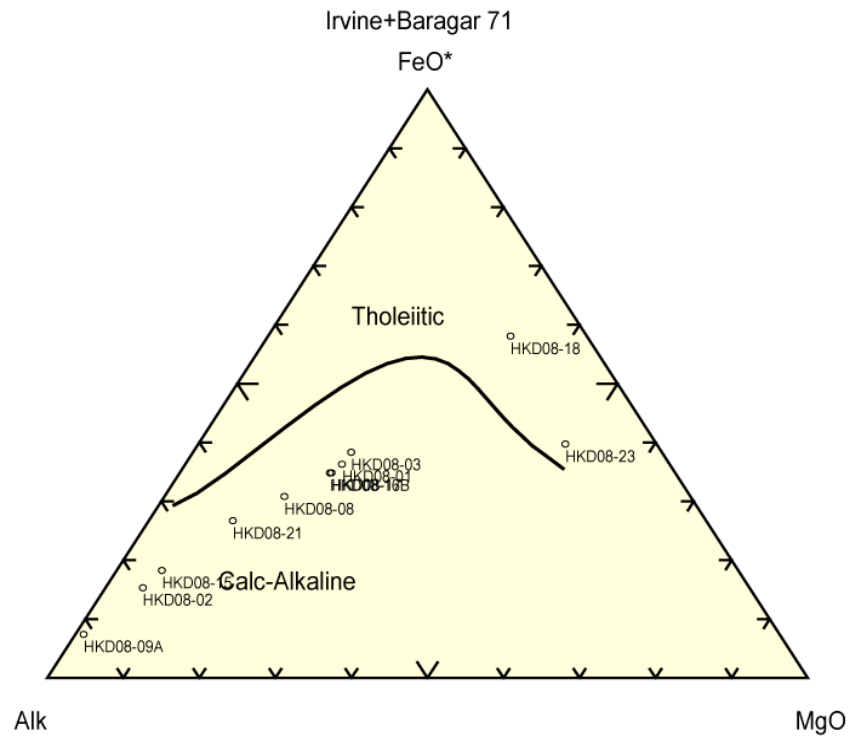
One of the most widely used major element classification diagrams is the FeO-MgO-Alkali (AFM) diagram. This diagram differentiate between tholeiitic and calc-alkaline magma series. Based on the plotted diagrams a clear trend is show for the granites and monzodiorites, which all falls into the calc-alkaline field. Chemical data from the two mafic enclaves/xenoliths samples falls into the tholeiitic field. This difference indicate that the granites and monzodiorites are more evolved than the mafic samples (Winter 2001). Based on the AFM-diagram in (Figure 22 a)), it seems likely that the HKD08-09A is the most evolved and the HKD08-03 is the least evolved of the calk-alkaline samples. The Hurry Inlet granite, described by Coe (1975), also plots in the calk-alkaline field in the AMF diagram (Augland 2007), and show a similar trend.

Based on the Shand's index (Figure 22 b)), most of the samples falls into the metaluminous field. All the monzodiorites falls into this area, while all the granites fall into the peraluminous area. Maniar and Piccoli (1989) have argued that mataluminous calc-alkaline magmatism, is typical for island arc- and continental arc-igneous suits, and also a $Al_2O_3/(Na_2O+K_2O)$ larger than 1.5 and 1.1 respectively (Table 10). As seen in the table, all samples have a typical arc signature. The same authors also indicate a area of SiO_2 wt % between 60-72 % for these types, but four of the monzodiorites falls under this estimate, which is out of the range for the discrimination criteria, based on granitoid rocks, made by Maniar and Piccoli (1989). Whether these discrimination criteria's can by of any use for the four samples in question is a matter of discussion, but since these samples clearly are granitoid, I will use the discrimination criteria as valid for these. The four samples I question all falls close or in the alkaline field, in the alkalis vs. SiO_2 diagram (Figure 23).

Sample	Al ₂ O ₃ /(Na ₂ O+K ₂ O)
HKD08-01	2,406639004
HKD08-02	1,865482234
HKD08-03	2,868338558
HKD08-08	2,092715232
HKD08-09A	1,422764228
HKD08-15	1,672433679
HKD08-16B	2,317880795
HKD08-17	2,346521146
HKD08-18	3,09540636
HKD08-21	1,962962963
HKD08-23	4,020618557

Table 10: A/NK ratios of the samples, indicating arc relationship (e.g. Maniar and Piccoli 1989).

a)



b)

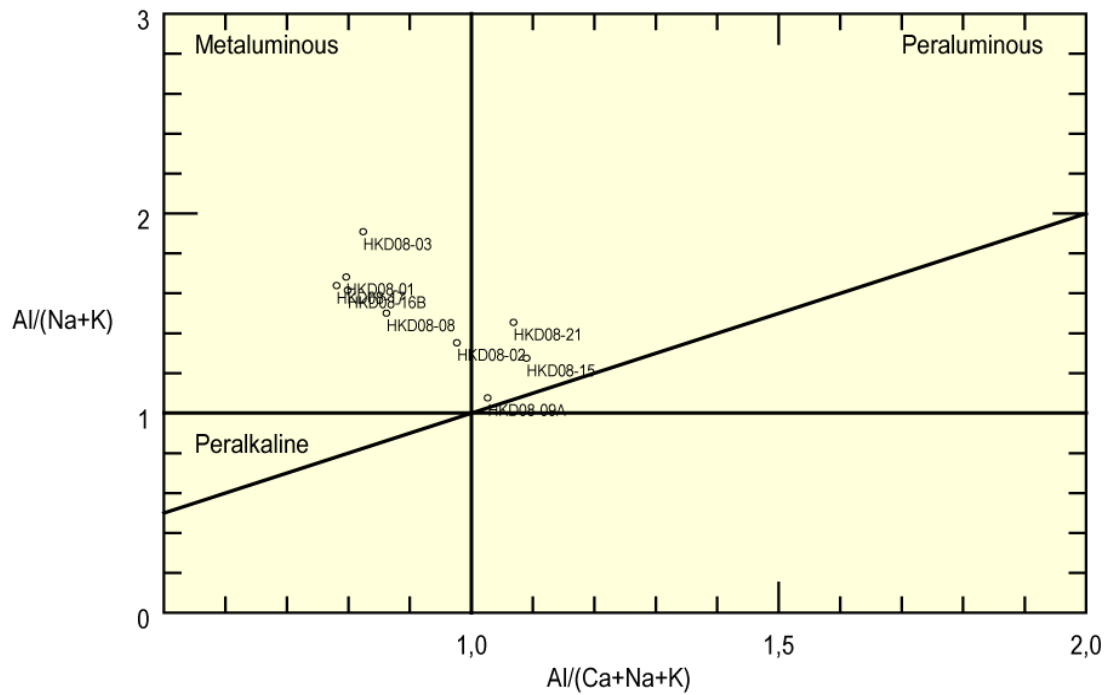


Figure 22: a) The samples are plotted in the AMF diagram, with discrimination between Tholeiitic and Calc-Alkaline from Irvine and Baragar (1971). b) Plots the rocks based on the Shand's index (Maniar and Piccoli 1989). Both diagrams are plotted in Iqpet.

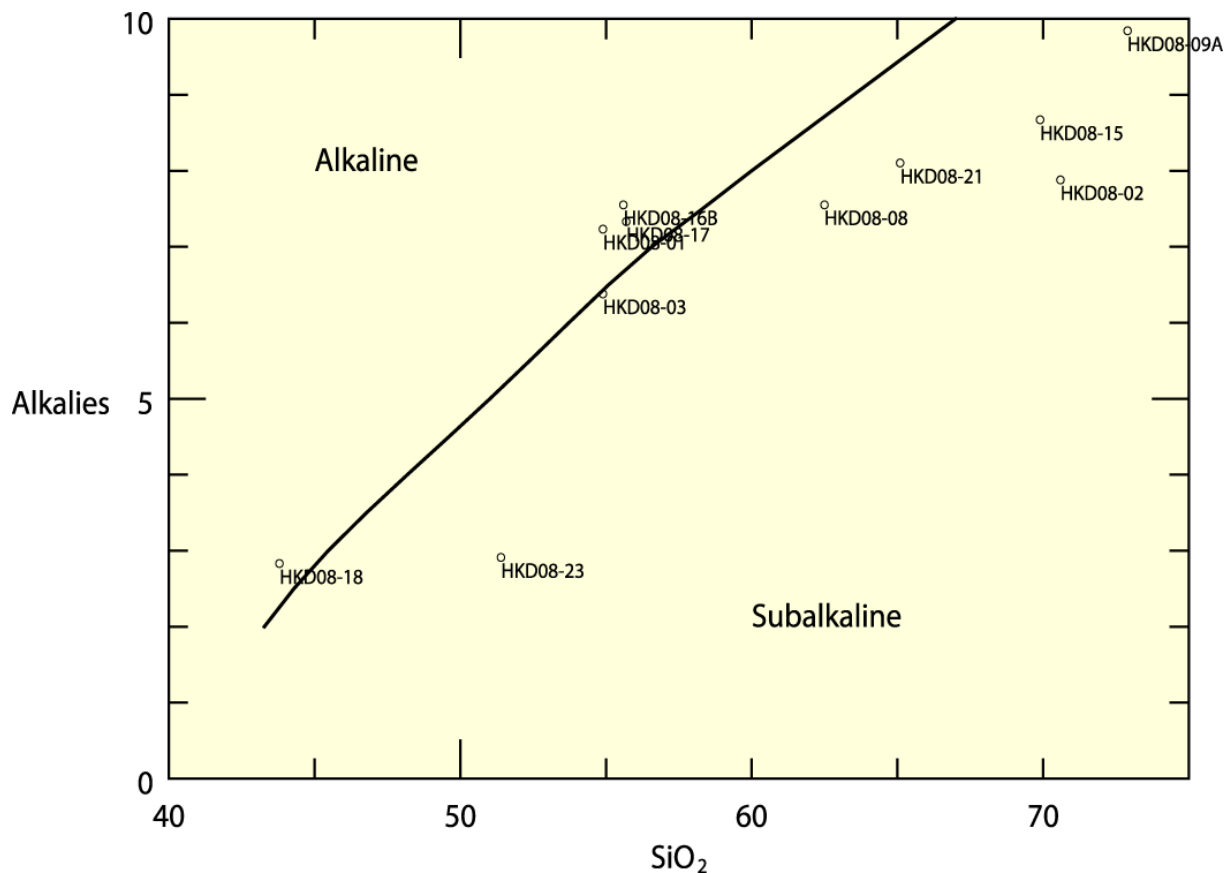


Figure 23: Alkalies vs. silica for the samples, dividing the alkaline from sub-alkaline rocks (Winter 2001).

On the Fenner diagrams (Figure 24), one can observe that all samples, except HKD08-18 and HKD08-23, fall on the same trend. The smooth trends on the Fenner Diagrams may suggest that the samples are related in some fashion (Winter 2001). The two mafic samples are separated from the granites, which suggests that they may have come from a different source. The mafic samples have less alkalies than the granites and monzodiorites, but have higher content of MgO and FeO. HKD08-18 also has a substantial higher amount of TiO₂ than the other samples. The mafic samples also have less SiO₂, which may indicate a source less saturated in silica or a more primitive source (Winter 2001). Since this study only contains 11 samples, the evolution of the melts are hard to state. The Fenner diagrams suggest that HKD08-18 and HKD08-23 have had a different evolution, or a different source than the granites.

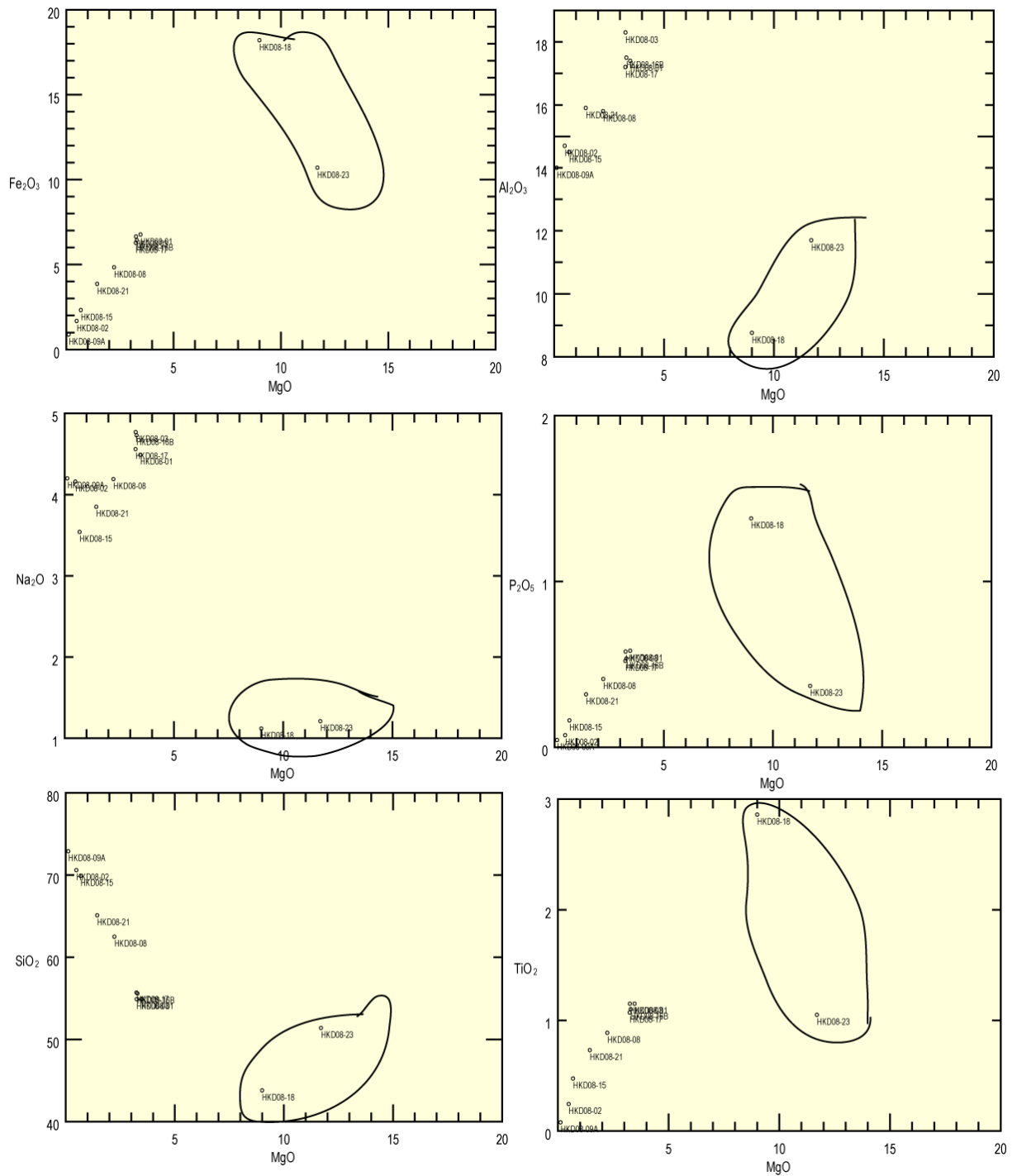


Figure 24: Main elements, from the XRF analyses, plotted in Fenner diagrams (Winter 2001). One can observe that the two mafic samples HKD08-18 and HKD08-23 stands out in contrast to the monzodiorites and the granites.

The Mg# ranges from 22.47 to 34.03 for the monzodiorites (Table 11). This indicates that these magmas are not from a primary source (Winter 2001). The Mg# also indicates that the HKD08-23 is the most primitive melt, which is in agreement with the AMF diagram (Figure 22 a)).

Sample	$Mg\# = 100 * Mg / (Mg + Fe)$
HKD08-01	33,82
HKD08-02	22,47
HKD08-03	32,83
HKD08-08	31,54
HKD08-09A	11,78
HKD08-15	22,74
HKD08-16B	33,85
HKD08-17	34,03
HKD08-18	33,09
HKD08-21	27,17
HKD08-23	52,23

Table 11: Mg# based on the XRF analyses.

All the granites, the monzodiorites and the mafic enclave/xenolith HKD08-23, falls into the Volcanic Arc Granites field (Pearce et al. 1984), whereas the mafic enclave (HKD08-18) falls into the Within Plate Granites field (Figure 25). They also tend to be more metaluminous than other East Greenland Caledonian granites (Figure 22 b)).

Based on the Rb vs. (Y+Nb) diagram used by Pearce et al. (1984), to discriminate granites according to their intrusive settings (Figure 25), we observe that all the samples, except HKD08-18, lies within the area of volcanic arc granites (VAG). The boundaries in the diagram are explained in Pearce et al. (1984) to be that ORG usually are derived from a depleted mantle source coupled with loss of Rb during magma evolution, WPG are derived from enriched mantle sources, amphibole fractionation often occurs during genesis of VAG and syn-COLG are enriched in Rb due to volatile inducement.

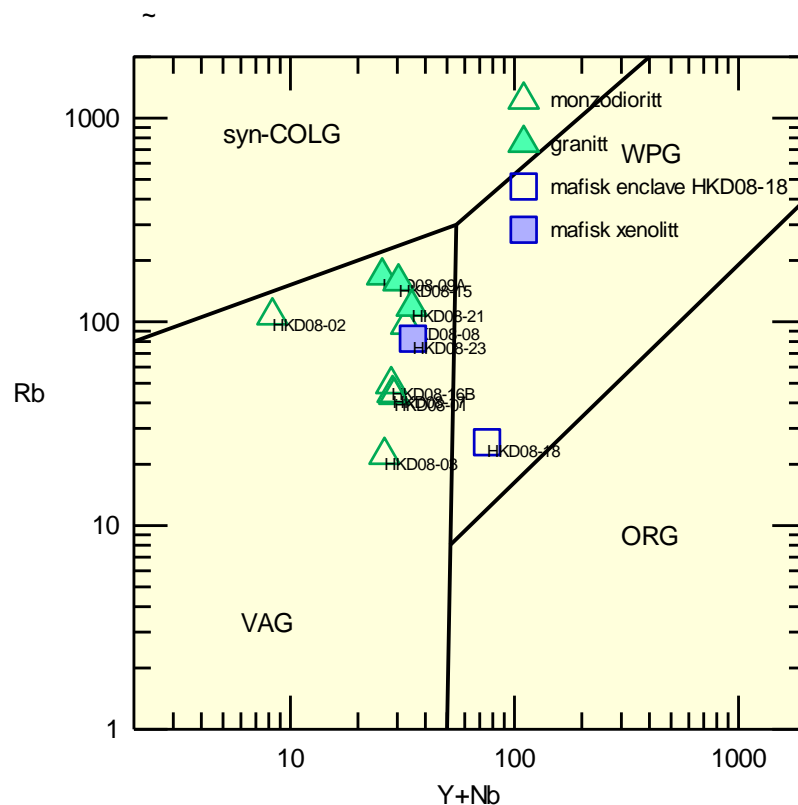


Figure 25: Trace element data from Liverpool Land plutons plotted in a Rb vs. Y+Nb discrimination diagram from Pearce et al. (1984) used to discriminate between granites of different tectonic environments. VAG: Volcanic Arc Granites, ORG: Ocean Ridge Granites, WPG: Within Plate Granites and syn-COLG: syn Collision Granites.

On the spider diagram (Figure 26), one can observe that all the samples have a negative Nb anomaly, which is characteristic for a subduction zone (Hickey et al. 1986, McCulloch and Gamble 1991, Winter 2001). The reason for this depletion is not very well constrained. Some attribute the low concentration of Nb to a residual Nb bearing mineral, such as hornblende (Morris and Hart 1983) in an OIB (ocean island basalt) source, while others such as McCulloch and Gamble (1991) attribute the Nb troughs to an addition of other, more compatible, high field strength (HFS) elements from neighboring rocks to a MORB (mid ocean ridge basalt)-like source.

Low abundance of HFS elements are common in tholeiitic and calc-alkaline arc magmas, compared to within-plate magmas (Murphy 2007). This same depletion can also be seen in the

dataset from Hurry Inlet granite (Coe 1975), which also plot's in the VAG area of the Pearce et al. (1984) (see above).

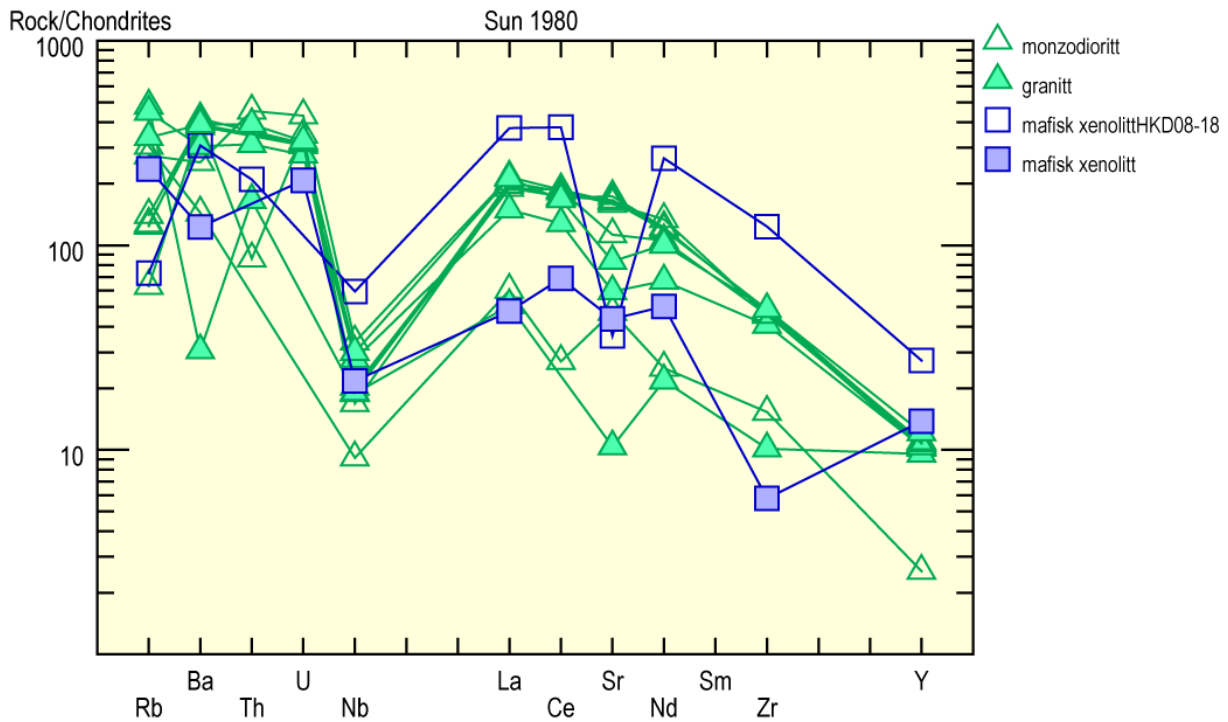


Figure 26: Trace element data from Liverpool Land plutons plotted in a spider diagram normalized to chondrite values from Sun (1980)

The monzodiorites have high Ba content, except HKD08-02 and HKD08-08, but no more than c. 1500 ppm, which is less than for the Hurry Inlet Granite, and also high Sr (up to 1900 ppm). Enrichment of these and other large-ion-lithophile elements (LIL) is consistent with slab involvement (McCulloch and Gamble 1991).

The monzodiorites are amphibole-bearing and are thus distinctly different from the “normal” S-Type granitoids from East Greenland, which consists almost exclusively of quartz, feldspars and mica (Kalsbeek et al. 2001b.). In contrast most of the granitic bodies on Liverpool Land has been emplaced into crystalline basement rocks (Coe 1975, Kalsbeek et al. 2008), as opposed to the S-types which were emplaced in the upper crust, including the low-grade the EBS. It is clear that there is a strong arc-signature to Liverpool Land rocks, as mentioned above (see spider-, AMF- and Shand’s index-diagrams). Melt is most likely generated by

partial melting (Petford et al. 2000), either of the mantle wedge or the down going slab. The heat are probably driven by either magmatic underplating or intraplate (Petford et al. 2000, Murphy 2007).

HKD08-18 seems to have a different source. It has clear negative Sr, Rb and Nb anomalies and a tholeiitic composition. The Sr anomaly may suggest that plagioclase hit liquidus quite early, which may also be the cause for the low amount of Al_2O_3 (Figure 24), while the Nb anomaly still is a characteristic of subduction related environments (Winter 2001).

As mentioned above, the presence mafic xenoliths and enclaves in granitic material, is a sign of magma mingling (Cole et al. 2001, Aslan 2005, Kumar and Rino 2006, Ventura et al. 2006, Lai et al. 2008), and is used to explain that homogeneity has not been obtained in the rock, as apposed to magma mixing (Lai et al. 2008). HKD08-23 and HKD08-18 could be examples of a mafic magma mingling with a more felsic magma.

6. ID-TIMS Geochronology

6.1 Analytical methods and sample preparation

The sample I prepared for ID-TIMS analyses was the HKD08-23, which is a mafic enclave, possible xenolith, surrounded and infiltrated by granitic material (Figure 17). This sample was taken from Liverpool Land, East Greenland in the summer of 2008. All the sample preparation and the analyses were done at the Institute for Geosciences at the University of Oslo, between September-November 2008.

Preparation was done by first crushing the samples to a maximum of 0,5 mm grains, then using a Wilfley table I washed out the dust and lightest minerals. The magnetic minerals was separated out by Franz, and the non magnetic, at 1,5A, fraction was poured in a heavy liquid (CH_2I_2 , DJM; $d=3.2 \text{ g/cm}^3$) and the heavies fraction was then poured in a dish with alcohol. I then picked out three different zircon fractions from this under a microscope, on the basis of morphology, transparency, color and internal textures (Corfu et al. 2003). The three different groupings of zircons is: 1) a tip and a flat part of a zircon crystal (Figure 27), 2) several short, but intact zircons with well developed crystal surfaces, some of them with possible inclusions (Figure 28), and 3) long prismatic zircons, most of them broken, but since they are long and thin, they most likely does not contain any inclusions (Figure 29). Of these three groupings I made four batches; one with the tip from 1), group 2) I divided into two and the last one was from group 3).

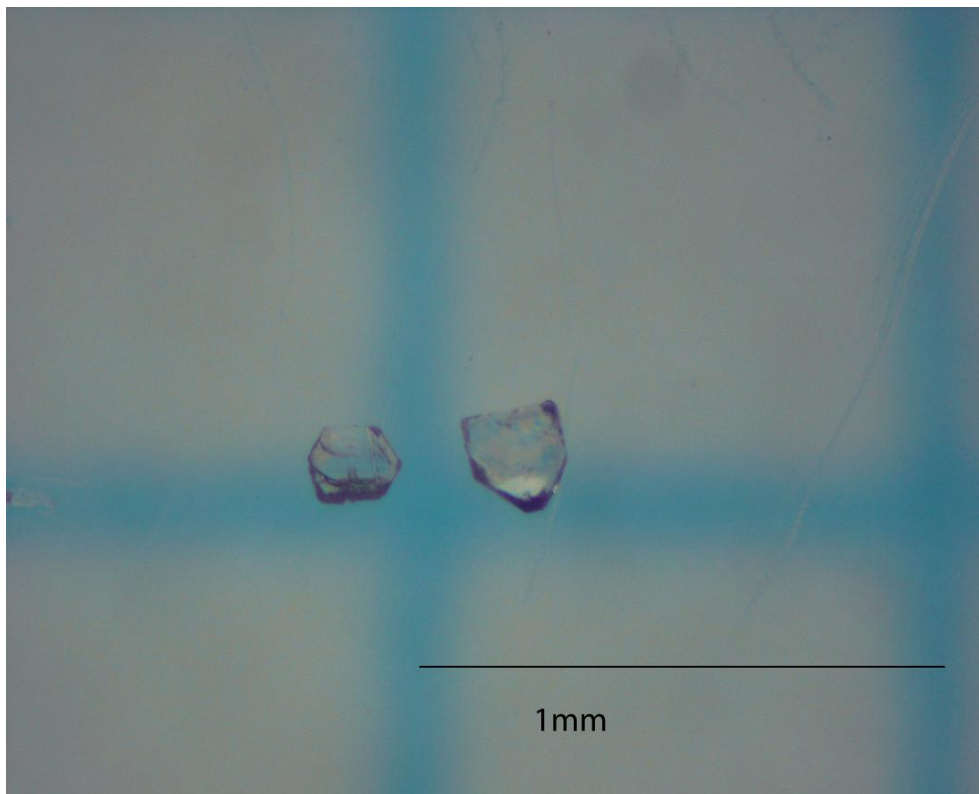


Figure 27: Photomicrographs of a tip from a zircon and a flat from another zircon, separated from a mafic enclave (HKD08-23)

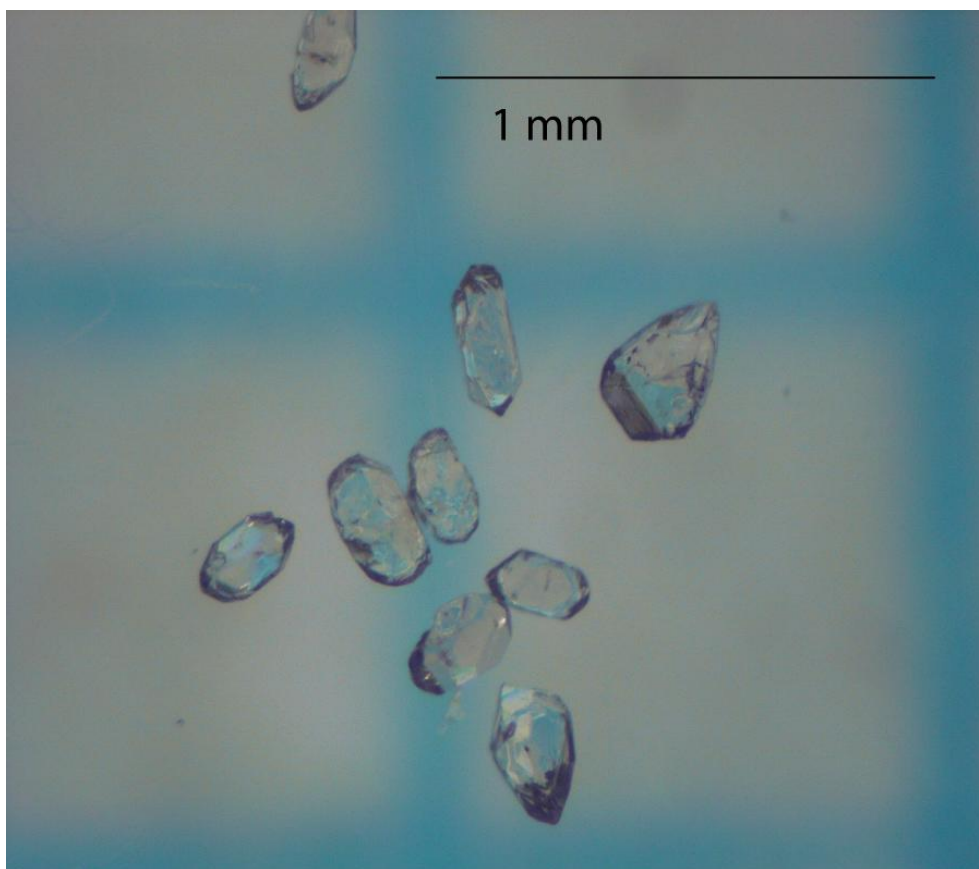


Figure 28: Photomicrograph of short stubby zircons, some containing inclusions.

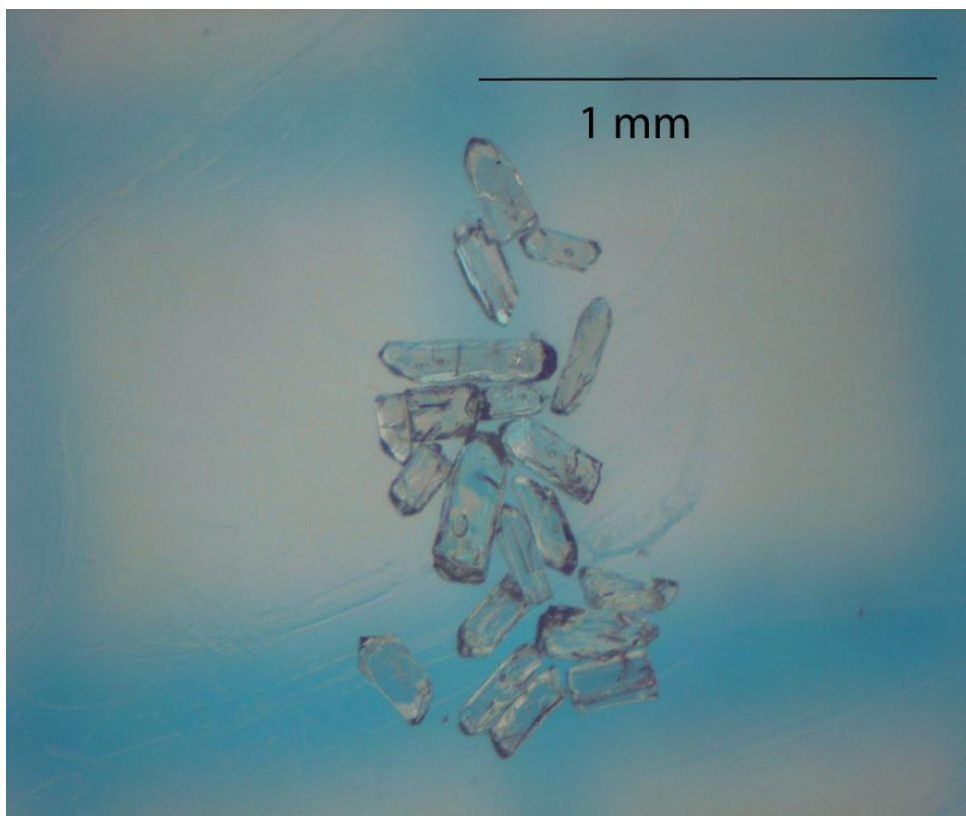


Figure 29: Photomicrographs of long prismatic zircons, without inclusion.

The grains picked out was then air-abraded by the method described by Krogh (1982a.), to removed the outer layers of the grains that may have experience led loss. The samples were then washed in a diluted HNO_3 , H_2O and acetone, to remove possible contamination. They where then weighed, and spiked, according to weigh, with a mix of ^{202}Pb - ^{205}Pb - ^{235}U tracer. This double Pb-tracer is added to determine the source of fractionation during measurements, that when added to the error calculations, gives better precision. The zircons was then dissolved in Teflon bombs at c. 190°C for c. 5 days in Hf and a drop of HNO_3 . After the dissolution, the zircons were chemically separated using micro-columns treated with anion-exchange resin (AG1-X8), were the solutions of zircon was treated with HCl to retain U and Pb in the resin. U and Pb were then extracted with HCl and H_2O , and mixed with a drop of H_3PO_4 and dried, before loaded on a Re filament with silica gel.

The measurements was done on a Finnigan MAT 262 mass spectrometer, using Faraday cups in static mode for high-intensity samples and Secondary Electron Multiplier (SEM) on low-intensity samples, in peak jump mode. The $^{207}\text{Pb}/^{204}\text{Pb}$ ratios on all samples were measured on SEM. All the SEM data were corrected for non-linearity based on standard measurements of NBS 982-Pb + U500, which was also used to monitor the reproducibility of the mass

spectrometer. The standard is always measured at the start of the day, before any other measurements. The analyses were done with series of 20 measurements for each element, using the Faraday cups, until the statistical dataset was good enough, and series of 10 measurements with SEM.

The measurements were corrected for a 2pg Pb and 0.1 pg U blank, with a composition of: $^{206}\text{Pb}/^{204}\text{Pb} = 18,3$, $^{207}\text{Pb}/^{206}\text{Pb} = 0,85$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15,555$. Corrections for common Pb were done using the Pb-evolution model of Stacey and Kramers (1975), based on the presumed age of the sample (c. 425 Ma). Fractionation of the U source was estimated to be 0,12 % a.m.u while the Pb fractionation was corrected with the measured $^{205}\text{Pb}/^{202}\text{Pb}$ tracer ratio, normalized to a certified value of 0,44050. If the $^{205}\text{Pb}/^{202}\text{Pb}$ ratio is very precisely determined and the fractionation corrections unrealistically precise, a standard fractionation error of 0,06 % a.m.u is incorporated. If the ratio is either far from 0,44050 or not determined, Pb fractionation is set to 0,1 % a.m.u.

Analytical errors and corrections were incorporated and propagated using ROMAGE 6,3, a program originally developed by T.E.Krogh (Table 12). Graphic presentation were performed with the ISOPLOT program developed by Ludwig (2003).

6.2 Analytical results

The analyses are quite concordant and they all fall within error (2σ) on $425,5 \pm 1.2$ Ma.

Fraction		HK-08-23 207/13	HK-08-23 207/14	HK-08-23 207/15	HK-08-23 207/16
Properties		Z	Z	Z	Z
Weight	[ug]	1	19	11	17
Pbt]	[ppm]	150	24	55	37
U	[ppm]	2200	354	820	546
Th/U		0,31	0,39	0,28	0,30
Pbc	[ppm]	1,27	0,11	0,57	0,09
Pbcom	[pg]	3,3	4,2	8,3	3,6
206/204		2873	6848	4595	11049
207/235		0,51874	0,51637	0,51422	0,51663
2 sigma	[abs]	0,01059	0,00123	0,00140	0,00124
206/238		0,06805	0,06770	0,06742	0,06771
2 sigma	[abs]	0,00138	0,00014	0,00015	0,00014
rho		0,99	0,92	0,89	0,94
207/206		0,05529	0,05532	0,05532	0,05534
2 sigma	[abs]	0,00015	0,00005	0,00007	0,00005
206/238		424,4	422,3	420,6	422,3
2 sigma	[abs]	8,3	0,8	0,9	0,9
207/235		424,3	422,7	421,3	422,9
2 sigma	[abs]	7,1	0,8	0,9	0,8
207/206		424,0	425,2	425,1	426,0
2 sigma	[abs]	5,8	2,1	2,8	1,9
Disc.	[%]	-0,1	0,7	1,1	0,9

Table 12: Analytical results from the ID-TIMS U/Pb analyses of the mafic enclave (HKD08-23). Fraction names are gives at the top (e.g. HK-08-23 207/13). Calculations were done with the ROMAGE 6.3 programme. Pbt: total Pb, Pbc: common Pb.

6.3 Geological interpretation

The analyses was done on a mafic enclave/xenolith, HKD08-23, located at 70°58.790'N and 022°23.057'W, Liverpool Land, East Greenland. The mafic body this sample was collected from was surrounded by and infiltrated by a more granitic rock. Three of the zircon fractions (207/14, 207/15 and 207/16) gives approximately the same age, within a small error (Figure 30). The 207/13 has a larger error than these three, which may be caused by the use of SEM for measuring the Pb_{207}/Pb_{206} ratio.

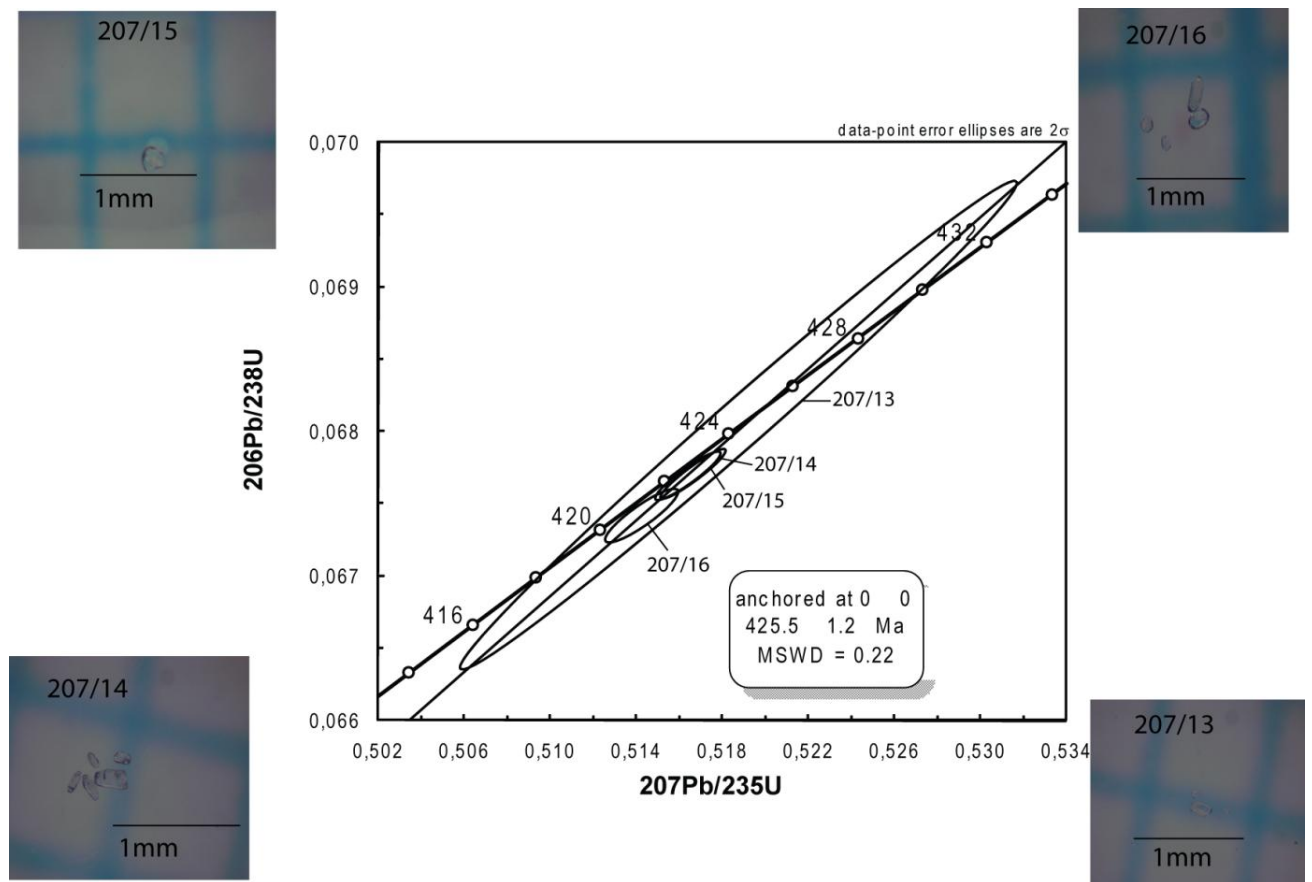


Figure 30: Concordia diagram of the HKD08-23, with microscope pictures of the different fractions, numbered according to table 7. The concordia diagram is anchored at 0, and gives a age of 425.5 ± 1.2 Ma, with a MSWD of 0,22. The error ellipse for each fraction is marked with the analysis number.

The % discordance of the samples are listed in Table 12 (as Disc.), and shows that the 207/13 is the least discordant sample (-0.1), but has the largest error. The discordance of the other samples are probably related to lead loss, but the discordance is so small, and they all fall close to the same age. So it seems very likely that the age of 425.5 ± 1.2 Ma is the crystallization age.

7 Discussion

7.1 Introduction

The purpose of this thesis was originally meant to try and document signs of older magmatism in Caledonian intrusives from Liverpool Land, as have been found in the Uppermost Allochthon in the Norwegian Caledonides, and also investigate the thrust drawn on the map from Coe and Cheeney (1972) (Figure 5). This apparent thrust was in fact not a thrust, but a late extensional fault, and thus not particularly interesting to this thesis. The mafic enclave or xenolith, which we hoped would show an older age than the granites was in fact of the same age, within error, as the emplacement age of the Hodal-Storefjord Monzodiorite, and thus we got a different answer than we would have hoped for. In this chapter I will sum up the analytical results from previous pages, and try to put the petrographic, geochronological and geochemical results in a larger regional context.

7.2 Tectonical and magmatic evolution of Liverpool Land Granites

7.2.1 Emplacement and tectonical environment

The granitic intrusives on Liverpool Land are (Hurry Inlet Granite and Hodal-Storefjord Monzodiorite), in contrast to the S-type leucogranites derived from the Krummedal Sequence further north in the East Greenland Caledonides, emplaced on a crystalline basement (Coe 1975). They also differ in mineral content, especially with the occurrence of amphibole and some reported orthopyroxene (Augland 2007). To put these granitic bodies in a larger regional context, they have been compared with data from granitoids from Renland (Augland 2007, Kalsbeek et al. 2008, Rehnström written comm.).

The granitoids in Renland shows the same calc-alkaline trend, as both the Hurry Inlet Granite and the Hodal-Storefjord Monzodiorite from this thesis, and the same trend on the spider diagrams, with the large negative Nb anomaly, a general depletion in the more incompatible elements and the fact that most of these granitic bodies falls into the VAG field, in the Rb vs. (Y+Nb) discrimination diagram of Pearce et al. (1984) (Figure 25). Though the Renland granitoids seem to have a more varied composition, and especially a slightly less negative Rb anomaly and often a negative Sr anomaly, the similarity both in petrography and chemical signatures are striking (e.g. Augland 2007, Kalsbeek et al. 2008, Rehnström written comm.). Newer U/Pb zircon ages from Augland (2007) shows that the older phase of the Hurry Inlet

Granite has the same age, within error, as the Danmark Ø Quartz-diorite in Renland, and the Hodal-Storefjord Monzodiorite have a similar age as some of the younger intrusives there (e.g. Rehnström written comm.).

Because isotopic data are not available from the Liverpool Land granites, isotopic data from the Renland granites might shed a light on the evolution of these granites (see above). Most of the Renland granites have a $\epsilon_{\text{Nd}(t)}$ value around -3 to -5 and nice defined cluster in the $\epsilon_{\text{Nd}(t)}$ vs. $\epsilon_{\text{Sr}(t)}$ diagram, except three of the younger granites, which are comparable in age with the Hodal-Storefjord Monzodiorite, and one leucogranite. They have a $\epsilon_{\text{Nd}(t)}$ between -8 to -11 (Kalsbeek et al. 2008). Together with the relative high SiO_2 content this suggest a strong crustal influence (Faure and Mensing 2005, Kalsbeek et al. 2008). The older granites from Renland, e.g. the Korridoren granitoid, correlated to the older phase of the Hurry Inlet Granite, is interpreted to be from a volcanic arc, related to the subduction of Iapetus under Laurentia (Kalsbeek et al. 2008). The range of $\epsilon_{\text{Nd}(t)}$ and the $^{87}\text{Sr}/^{86}\text{Sr}$ for the Renland granites show typical characteristics of I-type granites, which is also supported by the trace-element and petrographical data (McCulloch and Chappell 1982, Kalsbeek et al. 2008). Lu/Hf isotopic measurements from the Renland granitoids, yields a negative $\epsilon_{\text{Hf}(t)}$ values of < -8 , for the younger intrusions (Rehnström written comm.), which are consistent with melting and mixing of an enriched mantel source with continental rocks.

For the younger Renland granites, a model of fractionation of an incompatible element-enriched mantel source, with limited crustal contributions have been suggested. The Ba- and Sr- rich younger Renland granites have been fitted into this model, and may represent different stages in fractional crystallization of similar magmas. Two of the younger granites have significantly lower Ba and Sr and may thus have a different origin (Kalsbeek et al. 2008). The Hodal-Storefjord Monzodiorite have very similar Sr values but a higher Ba value than the Renland granites correlated with the “newer granites” of Scotland, which may suggest that plagioclase had not started crystallizing before emplacement, since Sr often replace Ca in plagioclase (Winter 2001, Faure and Mensing 2005).

The Hodal-Storefjord Monzodiorite show K/Na values of c. 0.3-0.9, with an average of c. 0.6 (Table 13), while the A/CNK value for the samples is c. 1.2-1.4 (Table 14). The A/CNK values of the Hodal-Storefjord Monzodiorite are higher than the similar granitoids from

Renland (e.g. Kalsbeek et al. 2008), while the K/Na values are in the same range. This gives further evidence of arc-related rocks (e.g. Winter 2001 and references therein).

Sample	K/Na
HKD08-01	0,610245
HKD08-02	0,894231
HKD08-03	0,337526
HKD08-08	0,801909
HKD08-09A	1,342857
HKD08-15	1,449153
HKD08-16B	0,596195
HKD08-17	0,607456
HKD08-18	1,526786
HKD08-21	1,103896
HKD08-23	1,404959

Table 13: The K/Na values of the samples, indicating I-type affinity (e.g. Maniar and Piccoli 1989).

Sample	A/CNK
HKD08-01	1,2841328
HKD08-02	1,4440079
HKD08-03	1,3738739
HKD08-08	1,3344595
HKD08-09A	1,3749754
HKD08-15	1,4902364
HKD08-16B	1,2829912
HKD08-17	1,2582297
HKD08-18	0,6571643
HKD08-21	1,5481986
HKD08-23	1,4028777

Table 14: This table shows the A/CNK values of the Liverpool Land samples, illustrates the metaluminous character.

According to Hickey et al. (1986) arc related rocks cannot be explained by one-stage partial melting of oceanic crust or of the mantel wedge, but components derived from the subducted

oceanic crust coupled with enriched asthenosphere or lithosphere, which is in good agreement with the evidence from above. The Silurian plutons from Renland/Milne Land are according to Rehnström (written comm.) formed by decompressional melting and upwelling of an asthenospheric mantle wedge, in response to an incipient orogenic collapse, which would thus suggest a similar emplacement for the Liverpool Land granitoids. This will be discussed at the end of this chapter.

Grampian Highlands

The younger Renland granites have by Kalsbeek et al. (2008), been compared to the “newer granites” and associated rocks of the Grampian Highlands of northern Scotland (Steinwoelf et al. 2008). These “newer granites” were formed during the post-tectonic stage of the Grampian Orogeny, when the Baltican plate was subducted under Laurentia, and comprise granites, granodioritic monzonites and monzodiorites. They are characterized by predominated by calc-alkaline composition with I-type affinity and trace element patterns with negative Nb and Ti anomalies, which has been interpreted as evidence for an active Andean-type setting (Steinwoelf et al. 2008). Based on the Shand’s index, they plot dominantly as peraluminous with a few samples falling into the metaluminous field, while the Hodal-Storefjord Monzodiorite are unambiguous metaluminous and the Hurry Inlet Granite plots in the peraluminous field (see above) (Steinwoelf et al. 2008). Trace element patterns for the “newer granites” of Scotland have generally larger negative Sr anomaly and a smaller Nb anomaly than the Liverpool Land Granites. $\epsilon_{\text{Nd}(t)}$ values from the subduction related granites in the Grampian Highlands range from c. -6.9 to -2.1, which is in the same range as the Renland granites, and suggest an arc related setting (Kalsbeek et al. 2008, Steinwoelf et al. 2008). It has been suggested a post-subduction related process for the magma generation of the “newer granites”, c. 430 – 390 Ma, in the Scottish Caledonides (Steinwoelf et al. 2008), likely derived from melting of earlier rejuvenated crustal sources.

Helgeland Nappe

Kalsbeek et al. (2008) also suggested a correlation between the Renland granites and Norwegian Caledonian granites (e.g. Bindal Batholite of the Helgeland Nappe Complex). The Caledonian intrusions in north-Norway are restricted to the Uppermost Allochthon and are assumed to be of Laurentian affinity. Younger magmatic plutonism in the Bindal Batholith,

are of the same age as both the Hurry Inlet Batholite, both old and young phase, and the Hodal-Storefjord Monzodiorite (Nordgulen et al. 1993, Augland 2007, Barnes et al. 2007). Isotopic studies and geochemistry of the Bindal Batholith indicates that a mixture of different crustal and sub-crustal rocks were involved in the magma generation (Birkeland et al. 1993, Nordgulen et al. 1993, Meyer et al. 2003), which is in agreement with the proposed setting for the Renland granites. The Bindal Batholith also range in composition from mafic gabbro to leucogranite and intrudes metasupracrustals of both Precambrian and Early Ordovician age (Nordgulen et al. 1993). The majority of the rocks of the Bindal Batholith are metaluminous and high-K calc-alkaline (Birkeland et al. 1993, Nordgulen et al. 1993). The $\epsilon_{\text{Nd}(t)}$ from the Bindal Batholite are in the range of -2 to -9 with most falling between -2 and -5, which is the same range as the Renland granites (Birkeland et al. 1993, Kalsbeek et al. 2008). Both these falls under the I-type granite criteria of McCulloch and Chappell (1982).

Other batholiths from the Helgeland Nappe Complex also show a similar trend (e.g. the Nesåa Batholith), with a clear volcanic arc signature in the Rb vs. Nb+Y from Pearce et al. (1984), but trace element trends are not correlatable, with much larger negative Ti anomaly and also a clear negative P anomaly (Meyer et al. 2003). Meyer et al. (2003) have suggested that the Nesåa Batholith may represent an early and possible marginal phase of extensive plutonism now recorded in the Bindal Batholith.

Kalsbeek et al. (2008) concludes that a more or less continuous granitic belt, may have been formed along the Caledonides from Scotland through East Greenland. A possible continuation through Norway to Svalbard also seems plausible, but later relative movements of the plates seems to have hampered precise correlation (Kalsbeek et al. 2008).

7.2.2 Mafic enclaves or xenoliths?

Mafic enclaves and/or xenoliths are generally interpreted as a sign of magma mingling, in contrast to magma mixing, where the magma is homogenized (Wilcox 1999, Cole et al. 2001, Kumar and Rino 2006, Ventura et al. 2006, Lai et al. 2008). In both the Hurry Inlet Granite and the Hodal-Storefjord Monzodiorite lenses of more mafic material are found, interpret to be enclave or possible xenoliths. According to Barker (2007) magma mingling is largely dependant on the style of magma emplacement. He states that nested plutons, plutons which is

feed by successive injections of magma into the interiors, allows for more effective magma mixing and mingling, while sheeted plutons, which grow as new magma follows contacts between wall rock and earlier intrusions, do not promote magma mingling or mixing but allows for more wall rock assimilation (Barker 2007). Sheeted plutons will often lead to trains of xenoliths aligned with the external stratigraphy. In the Liverpool Land granitoids there are lots of mafic enclaves, these do not align and they have the same age (within error) as the granitoids. It seems unlikely that they are xenoliths. This would rather argue for a magma mingling process, where the more mafic magma solidified a little earlier than the felsic magma. Thus it is plausible that both the Hodal-Storefjord Monzodiorite and the Hurry Inlet Granite plutons have undergone endogenous growth (nested plutons) (e.g. Barker 2007).

Xenoliths are described as a piece of country rock, incorporated in the magma as it rises, while enclaves are a more general term for mafic inclusions (Winter 2001). Whether the mafic samples, HKD08-18 and HKD08-23, are xenoliths is a matter of discussion. Enclaves, on the other hand, have been interpreted by Vernon (1984) to represent globules of mafic magma that have mingled and quenched in granitic magma. He also proposed that they share the same composition, as the host granitoid but with a different mineral assemblage. Based on the AMF diagram (Figure 22 a)), it could very well be that these inclusions are from a different and more primitive source, since they have a tholeiitic composition. On the other hand they have a similar trace element trend, on the spider diagram (Figure 26) and HKD08-23 have the same age (within error), c. 425 Ma (see chapter 6), and falls into the same field in the discrimination diagram from Pearce et al. (1984) (Figure 25) as the Hodal-Storefjord Monzodiorite. The origin of the enclaves are not well established and a matter of speculation, as magma mingling only shows that magmas of different compositions can coexist and not how they originated (Vernon 1984). Even though, Vernon (1984) proposed three different origins of mafic enclaves, 1) from partly crystallized and quenched margins of the granitoid, 2) repeated injection of more mafic magma into the granitoid, or 3) a mafic layer in the pluton, which is partly mixed with the granitic magma. Isotopic studies of both the mafic enclaves and the host granitic rocks could shed more light on the relationship between the enclaves and granitoids.

It seems likely that these enclaves represent globules of mafic and more primitive magma mingled and quenched in a granitoid host magma, since they have the same age and share

quite a lot of the chemical signatures (e.g. Nb anomaly, have the same VAG signature and shear the subalkaline or close to subalkaline trend).

7.3 Emplacement of the Hodal-Storefjord Monzodiorite

Rehnström (written comm.) propose a model of decompressional melting of upwelling asthenospheric mantle, as a response to orogenic collapse, for the generation of the Renland granitoids. This is based on $\epsilon_{\text{Nd}(t)}$ values (> -8 for the older group and < -8 for the younger group) which suggest a mixed mantle and crustal source. She also back up this argument with the presence of Mesoproterozoic xenocrystic zircons and fractions, found in these granites. Further Rehnström (written comm.) argue for extension based on the presence of 420 Ma lamprophyres intruding the Krummedal Sequence (e.g. Andresen et al. 1995), which could have caused an orogenic collapse and thus lead to the decompressional melting. Extension in the East Greenland Caledonides, have been documented in the upper crust coupled with compression in the lower crust (Andresen et al. 2007), and I question if this extension is enough to cause decompressional melting of the mantle wedge. Lamprophyres of this age have not been documented on Liverpool Land, and there are no documented signs of extension in the time of emplacement of both the Hurry Inlet Granite and the Hodal-Storefjord Monzodiorite. Neither xenocrystic zircons nor other fractions been documented, and thus the argument that melts from Renland have been derived from an older protolith is probably not valid for the Liverpool Land granitoids. Another model for melt generation is a suprasubduction model in which dehydration of the subducting slab, leads to partial melting of the mantle wedge (e.g. Tatsumi 1989, Murphy 2007). This melt would then be more buoyant, and thus rise, giving rise to mafic magma underplating the crust, which again would give of enough heat for partial melting of the lower crust. This model also allows for mixing of mantle and crustal rocks, thus giving the isotopic signatures presented for the Renland granites (e.g. Kalsbeek et al. 2008, Rehnström written comm.) (Figure 31). This could also explain the occurrences of the mafic enclaves, as part of this magma may have mingled with the more felsic magma as the crust is heated.

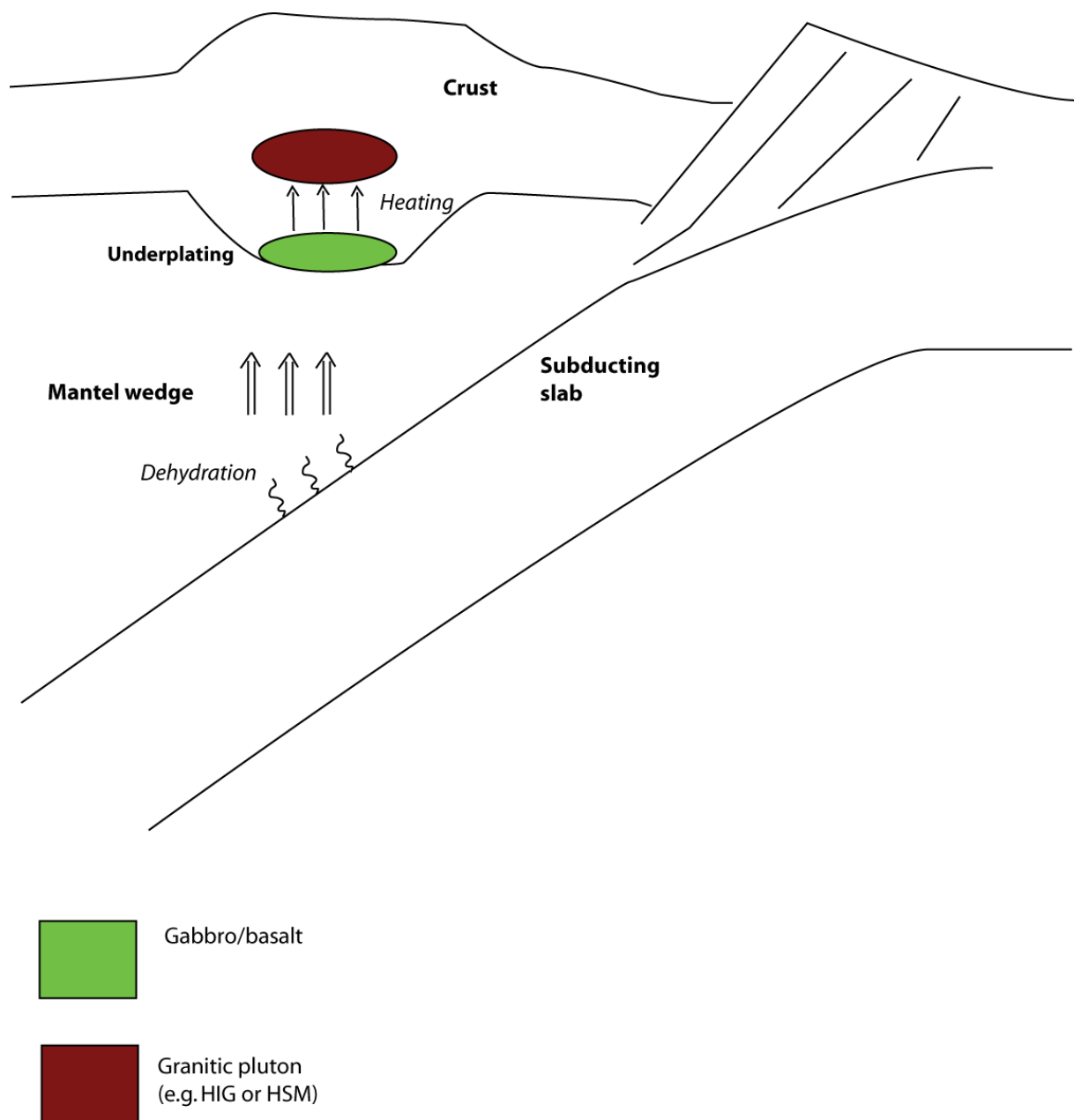


Figure 31: A simplified schematic figure (not to scale) of the proposed process leading to the emplacement of the Liverpool Land granites. Dehydration of the subducted slab causes partial melting in the mantle wedge, generating a gabbroic pillow in the lowermost crust. This causes enough heat to generate partial melting in the lower crust, leading to granitic plutons. HIG:Hurry Inlet Granite, HSM: Hodal-Storefjord Monzodiorite.

Based on the lack of evidence for extension in Liverpool Land, I would prefer the suprasubduction model for these granites.

Further isotopic studies of the Liverpool Land granites would help shed more light on the tectonical evolution.

8 Conclusion

Based on the evidence, presented above, it seems quite clear that the Liverpool Land intrusions were emplaced in an arc system, related to the subduction of Baltica under Laurentia at early Silurian age (c. 425 Ma). This caused a dehydration of the Baltican crust subducting under Laurentia, leading to partial melting in the mantle wedge and underplating of the crust. This extra heat started melting of the overlying crust, which created the Liverpool Land I-type granites. Mafic magma from this underplating may have then mingled with the felsic magma, giving rise to the many mafic enclaves observed in these intrusives. Isotopic evidence from the Renland granites, which share both age and geochemistry with the Liverpool Land granites, further supports this theory. These granites are correlatable with granitoids from both the Scottish and Norwegian Caledonides, which could suggest a wide stretched granitic belt across most of the Caledonides. The Liverpool Land granites have a clear subduction related signature, and a clear arc setting is evident.

The mafic enclave (HKD08-23) is of the same age as the Hodal-Storefjord Monzodiorite (c. 425 Ma), and show the same trace element trends. It's occurrence points to a process mingling of felsic and mafic magma.

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